DYNATECH R/D COMPANY

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COST ANALYSIS OF AQUATIC BIOMASS SYSTEMS

- Final Report -

Prepared by:

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Thomas Hruby, Woods Hole Oceanographic Institution
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John R. Benemann, CSO International Inc.
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W.J. Oswald, CSO International, Inc.
Judson G. Brown, Consultant

July 25, 1978

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a division of DYNATECH CORPORATION

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ABSTRACT

A cost analysis of aquatic biomass systems was conducted to provide the U.S. Department of Energy with engineering cost information on which to base decisions in the area of planning and executing research and development programs dealing with aquatic biomass as an alternative energy resource. Calculations show that several hundred 100 square mile aquatic biomass farms, the size selected by DOE staff for this analysis, would be needed to provide meaningful supplies of energy. It should be noted that systems which require wastes (sewage, power plant CO_2) as a carbon source, natural harbors or lakes, and natural upwelling sites may not have application to the present study simply because they are very small compared to the large needs projected by DOE.

With this background, specific engineering analyses were conducted on two original design concepts for 100 square mile aquatic biomass energy farms. These systems were an open-ocean system and a land-based system; outstanding experts in all aspects of this project were called upon to participate and provide information in projecting the costs for harvested aquatic biomass for these systems.

It was found that the projections of costs for harvested open-ocean biomass, utilizing optimistic assumptions of scientific and engineering design parameters, appear to be above any practical costs to be considered for energy. One of the major limitations is due to the need to provide upwelled sub-surface water containing needed nutrients, for which pumping energy is required. It is shown that for lower yields of biomass, the energy in ocean waves may marginally provide energy to pump suitable amounts of upwelled water for nutrient supply; however, costs of harvested biomass are very high at lower yields. On the other hand, for projections of biomass growth at increasingly higher yields, so much nutrient containing water is required that environmental wave energy is insufficient and fuel or electric power is required for pumping; thus, with high yields, obtaining a net positive energy balance from the open-ocean farm becomes tenuous. Further, there are very substantial environmental and legal aspects of aquatic biomass farming in general that appear especially ponderous for an open-ocean system.

It is concluded from this analysis that large scale land-based aquatic biomass farms may merit development, but perhaps within a much narrower range than heretofore investigated. For example, land-based aquatic biomass systems based on biomass which require a carbon source other than carbon dioxide from the air appear to have higher costs than may be acceptable as an energy resource. Sewage sludge appears to have limited availability as a carbon source for many energy farms and the utilization of CO_2 from power plant stack gases requires duct work and distribution system which are prohibitively costly.

Aquatic plants which appear to have potential for development as an energy resource are the so-called emersed plants, or angiosperms, including many types of freshwater weeds such as duckweed, Hydrilla, and water hyacinths. It is recommended that substantially greater basic and applied knowledge on these aquatic biomass are needed, especially on growth rates and nutrient requirements.

This present cost analysis has met the intended objectives of the Department of Energy in providing information on which to base program planning decisions. The National Workshop on this project, held January 24-25, 1978 under the auspices of the Marine Industry Collegium at MIT, provided a forum for presentation and discussion of these summary conclusions and recommendations.

FOREWORD

The prospect of deriving fuels and chemicals from algae and other aquatic plants has aroused intense interest among those with needs and responsibilities for the development of alternative fuel and material sources. A basic reason for this interest is the fact that it can be projected that enormous quantities of such plant material could be derived from land or sea areas not now utilized intensively for other purposes. Few other schemes for resolving our problems of fuel/chemical supply appear to tap so simply and directly a resource so vast and non-competitive with other human activities. Accordingly, aquatic plant growth and utilization merits careful examination. The purpose of this report is to furnish factual material which may be used to determine how aquatic plant cultivation can be practiced, what the costs of such operations will be, and the nature of problems that must be resolved if the process is to be successful.

In working to meet these objectives we are dealing with huge engineering undertakings, involving technology either never before practiced or never carried out on the scale projected. It is understandable that analyses of such systems involves the development of assumptions about functioning and assumptions about costs. Under these circumstances the assumptions and the conclusions drawn must carry some degrees of uncertainty. The consequences of divergence from the assumptions made may be evaluated through the sensitivity analysis presented.

The intensity of interest in the culture of aquatic plants and the recognition of the uncertainties involved have fostered the development of disagreement about its merit. The analyses presented in this report will provide a conservative basis from which to judge the feasibility of process propositions for aquatic plant culture. In this respect attention is drawn especially to the key factors of growth rate and nutrient supply. This report offers for these and other factors base-line figures which may be utilized in judging the technical and economic impact of any advocated departures from the base-line. As such, the work will provide its intended function as a rational basis for prudent decisions whether aquatic plant culture currently presents an opportunity to be capitalized upon or an uneconomical investment in our national energy program. Of equal importance is the value of the analysis in identifying areas of research that may resolve problems which render the presently available technology uneconomical.

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Section 1

INTRODUCTION

This is the final report on the contract "Cost Analysis of Algae Biomass Systems" which was competitively awarded to Dynatech R/D Co. on June 27, 1977 by the U.S. Department of Energy, Fuels from Biomass Systems Branch, Division of Solar Energy Technology. The purpose of the work presented here was to provide the Department of Energy with a practical enginering assessment of the costs of growing and harvesting essentially any type of aquatic biomass, that is, any organic matter that may be grown in any type of water, then harvested and used as an energy source. To date, the Fuels from Biomass Systems Branch of DOE has carried out similar studies based on a) carbohydrate crops (this has included sugar cane, sugar beets, corn, and sorghum); b) grains and grasses; and c) silvicultural crops. This present work, therefore, is to report on the last major "crop grown" biomass not heretofore considered, namely, aquatic plants. It is to be pointed out that system studies have also been carried out by DOE on biomass residues, namely a) animal residues, e.g., cattle feedlots and dairy farms; b) crop residues, e.g., corn stover, grain straws; and c) wood/forest residue. In perspective then, this present work completes a very broad evaluation by the U.S. Department of Energy to investigate the full potential for biomass as an alternative energy resource.

In setting forth the objectives for this present study, the original "Request for Proposal" called for a very broad investigation of all aquatic grown biomass. With respect to a physical structure or design concept this included biomass that might be grown in open ocean, near-shore, shore-line, and in distinctly land-based systems. Likewise, the water in which to grow aquatic biomass was marine, brackish, or fresh water. Perhaps the only specific design criterion stated in the RFP was that any biomass system concept be 100 square miles.

The usefulness of this report is not intended to be limited to those interested in biomass only as an energy resource, although the thrust of this work is clearly oriented to large scale energy farms. The costs presented here for harvested aquatic biomass are based on specific plant growth rates and in systems of modular design. If the specific interest is in recovery of certain chemicals from the aquatic biomass, or in the conversion of the harvested aquatic biomass into chemicals, then this report will be of assistance to the process engineer. No processing costs of any type were considered here, however, because the objective was entirely to provide reasonable cost estimates on the process feedstock - harvested aquatic biomass.

It is to be noted that engineering concepts based only on presently available technology and current scientific knowledge is considered. Plant mutations to achieve high growth rates, symbiotic systems providing rapidly growing plants with nitrogen-fixing companion plants, and other possible scientific breakthroughs are not part of this analysis.

1.1 Biomass Sources and Potential Energy Contribution

A program for development of fuels from biomass should consider all forms of plant material, both those grown on land (terrestrial) and those grown in or on water (aquatic). It should include forest and crop residues and animal manures, as well as crops grown for their energy content on energy farms. It has been estimated by the U.S. Department of Energy that the energy value to be produced by fuels from biomass is 0.5 quads in 1985, 3 quads in 2000, and 10 quads in 2020. Production at that level will provide 0.5 percent, 2 percent, and 5.6 percent of the total projected U.S. energy demand for those years, as estimated in 1975.

If an aggressive demonstration program is carried out on a national scale, it is estimated that biomass production of useful energy can be accomplished on a regional basis at competitive costs and can be of significant benefit in terms of its contribution to the solution of national energy problems. For example, the 1977 national demand for gasoline was 80 billion gallons per year; for natural gas, 23 trillion cubic feet. Biomass may supply up to 10 percent (3.5 quads) of those 1977 requirements by the year 2000. A promising market for biomass fuels appears to be the transportation sector, because of its size and criticality. Next in importance in terms of energy demand may be the large industrial, commercial, and residential market for natural gas. Other possible markets for biomass-based energy are a) some portion of the petrochemical industry, b) small electrical utility plants that currently use oil or natural gas and c) industries that use steam for heat.

Because biomass contains 30 to 90 percent moisture and has low densities relative to other feedstocks such as coal, transportation costs become a significant factor in the price of biomass delivered to the conversion site. Therefore, it may be necessary to locate conversion facilities near the source of the biomass.

In Figure 1.1 and the supportive data in Table 1.1 are shown current estimates of the availability and characteristics of various biomass resources. The most significant projected source of terrestrial biomass is hardwood trees grown and cultivated on energy farms. Energy farms will use intensive management techniques aimed at maximizing yields and minimizing the production cost of biomass. Important factors in planning these farms include land aggregation, biomass species selection, water availability, and management strategies for growth and harvest.

It is noted in Figure 1.1 that residues from lumbering, field crops, and animals represent a finite and significantly smaller resource base than that from any types of energy farms. However, until a long-term supply of biomass is ensured by the establishment of energy farms, these residues should be used because of their more immediate availability.

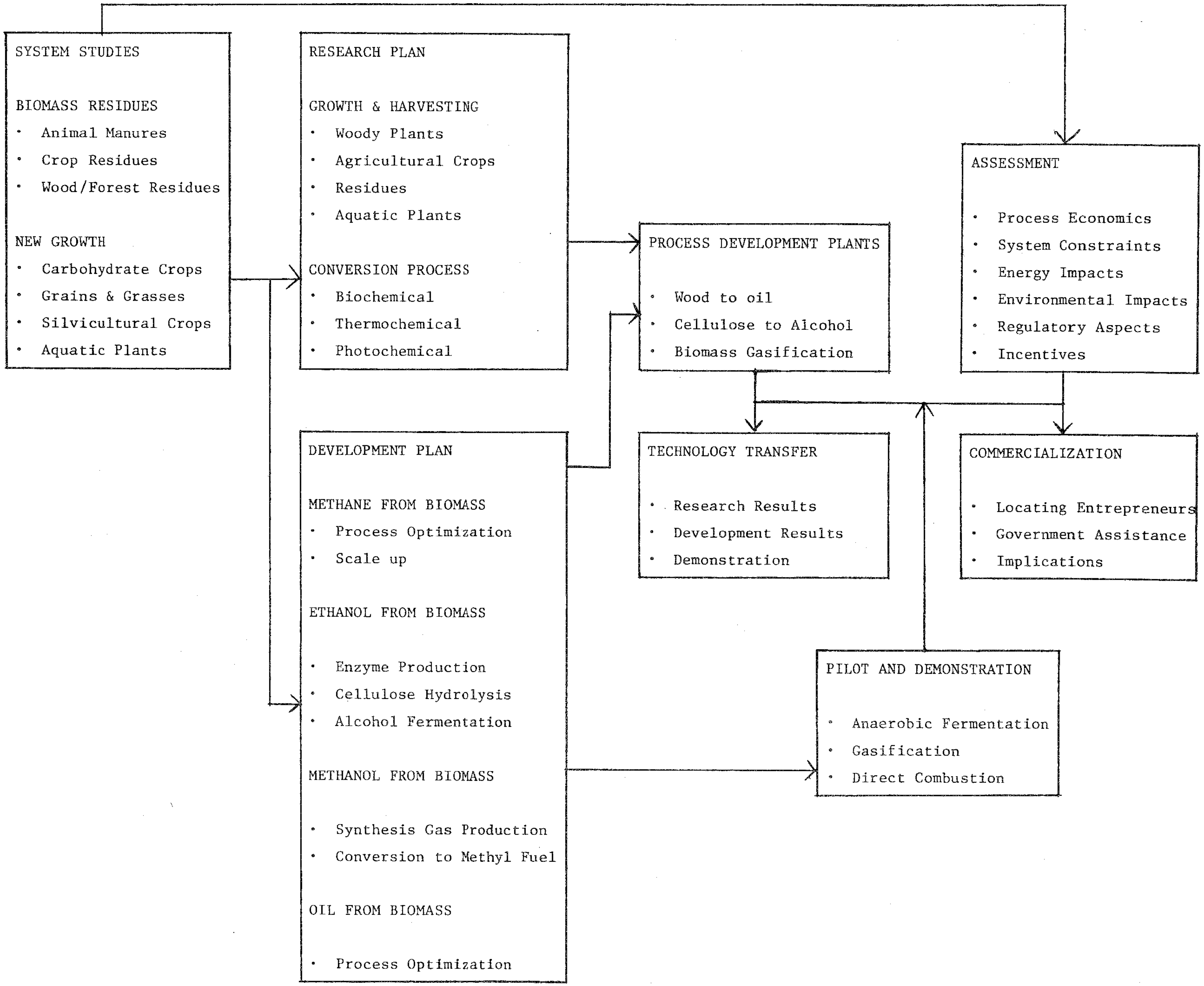


Figure 1.1

Element Structure of U.S. Department of Energy Fuels From Biomass Program
(from U.S. Department of Energy, courtesy Dr. Roscoe Ward)

Table 1.1

Characteristics of the Biomass Resource

(from U.S. Department of Energy, courtesy Dr. Roscoe Ward)

Type of Biomass	Availability: Theoretical	Availability: Practical	Regionality	Degree of Seasonality	Sensitivity of Availability to Price (at roadside) Supply Elasticity*	Relative Size of† Useful Farm (acres 000)
Agricultural and Forestry Residues	427 million tons	100 million tons at less than $25/ton	Follows crop live-stock and forest harvesting patterns	Production in late summer or fall; however, material will be storable	0.83	85 to 170
Terrestrial Energy Crops	206 billion tons	100 - 300 million tons at less than $25/ton	Total United States	Late summer or fall or year round depending on location and species	2.5	17
Aquatic Energy Crops	NA	NA	Coastal areas and open ocean	Year round production		NA
Standing Vegetation	1 billion tons inventory	20 million tons/year at less than $25/ton	Primary forest lands and high rainfall areas	10 month season depending upon weather	1.25	34 to 170

* $\frac{\%\Delta Q}{\%\Delta P}$ = Supply elasticity - (increase in quantity divided by increase in price).

† Yield assumption tons per acre = Residues -- 1 to 3 oven dry tons (ODT) per acre, terrestrial crops = 15 ODT/acre, standing vegetation = 1 to 4 ODT/acre.

There are many uncertainties regarding the farming of aquatic plants for energy but the large areas potentially available justify pursuit of this technology. Projection of the relative amounts of energy, as seen in Table 1.1, may be comparable to terrestrial energy farms. As will be seen in this report, due to the factors involved in growing aquatic biomass and the 200-mile limit, even open ocean systems may have limited area considerations. On the other hand, land-based aquatic biomass energy farms may either compete with dry land grown energy crops or find special applications. Some consideration of these resources is in order.

1.2 Impact of Biomass Energy Farms on Energy Needs

While the orientation of this present project is to establish cost guidelines for growing and harvesting aquatic biomass, up to the point of processing, it is clear that processing of the aquatic biomass to methane via anaerobic fermentation is a reasonable conversion process to consider. Due to the high water content of aquatic biomass and the lack of any major comminution requirements, anaerobic fermentation appears the likely choice as a conversion process. Thus, to consider the impact of aquatic biomass on our nation's energy needs, as well as investigation of what may be the magnitude of this energy contribution, it is well to look at other processes competitive to anaerobic fermentation for methane production.

For a long time efforts have been underway to gasify coals. At the present time, coal gasification plants are being planned for producing 250 MMCF methane/day (250 million cubic feet/day), which will consume approximately 33,000 tons/day of coal. Each one of these plants has been stated to be larger than the world's largest oil refinery. Many of these coal gasification plants appear to be needed. For example, to supply 25% of our nation's present natural gas consumption of over 20 trillion cubic feet of methane per year, i.e., 5 trillion cubic feet CH_4/year (5 quads), it may readily be calculated that 55 of these large coal gasifier plants will be required. Since coal gasification technology is reasonably well advanced, and there is a ready supply of coal in the United States, it is clear that any alternative fuel gas production technology, such as anaerobic fermentation of aquatic biomass, will need to be compared with coal gasification.

A first calculation in considering fuel gas from aquatic biomass technology as satisfying meaningful fractions of our nation's needs is that of ascertaining the land area or ocean area requirements to produce an amount of biomass that may be converted to 250 MMCF CH_4/day. A practical value for aquatic biomass production on a full-year basis (as opposed to higher reported values based on short times and then projected over a full year) is 10 tons (dry ash free)/acre·year. It will be further assumed that the aquatic biomass may be harvested and converted to methane (where stoichiometrically, 1 lb. cellulose $\rightarrow$ 6.65 ft^3 CH_4) at a 50% total efficiency. As noted earlier, an energy farm of 100 square miles (64,000 acres) is assumed. It may be shown that, with these assumptions, one 100 square mile aquatic biomass farm may be able to provide organic matter for conversion to approximately 12×10^6 ft^3 CH_4/day and that approximately 20 of these energy farms will be required to equal the methane production from one large coal gasification plant. Note that the energy farm to coal gasifier ratio of 20/1 is independent of being land-based or open ocean based.

A further calculation is the maximum number of energy farms that may be constructed and the subsequent fraction of total methane consumption that may be supplied with these large numbers of farms. For land based systems, it was shown above that 95 million acres of land may be available in the United States. Devoting all this land to aquatic biomass energy farms, each of 100 square miles (64,000 acres) will enable 1500 of these energy farms to be built. Since about 20 farms are needed to equal the production of one coal gasifier, the potential exists for aquatic energy farms to equal the production from 75 large coal gasifiers thus supplying approximately 35 percent of our nation's present natural gas consumption. While clearly many more factors enter into actual decision making, the satisfying of meaningful fractions of energy needs may thus be projected with land-based aquatic biomass energy farms.

Because of the logistics of harvesting biomass it may be assumed that many smaller fuel production plants will be needed. If a feedstock biomass of 5000 tons/day (1.8×10^6 tons/year) is assumed as a baseline plant size then, consistent with the above assumptions, an area of 285 square miles will be required, i.e., almost three of the base-line 100 square mile biomass farms will be needed to supply a 5000 ton/day processing plant - the production of this plant will be approximately 34×10^6 ft^3 CH_4/day. These calculations are independent of the energy farm being land-based or open-ocean based. To compare with coal gasification, where 55 large plants could produce 25% of our present natural gas needs, it is seen that 400 facilities processing 5000 tons/day of aquatic biomass are needed, each 5000 ton/day plant being supplied by almost 3 - 100 square mile biomass energy farms.

To compute the maximum potential contribution from open-ocean farming it was shown above that a maximum of 200,000 square miles of open-ocean may be available for biomass farming. Thus, an upper limit of 2,000 open-ocean farms of 100 square miles size may be constructed. This compares well with the projected number of land-based farms of 1500 of this same 100 square mile size. On the same basis as shown above it may be calculated that a maximum of 47 percent of our nation's present natural gas consumption might come from open-ocean farming; this is comparable with the 35 percent calculated for land-based systems. In summary, in Table 1.2 is presented a comparison between coal gasification and anaerobic fermentation of biomass.

Table 1.2

Comparison of Aquatic Biomass Energy Farming with Coal Gasification

Comparison	Coal Gasification	Anaerobic Fermentation of Aquatic Biomass (from Open Ocean or Land Based Aquatic Energy Farms)
Assumed plant size	33,000 tons coal/day	5,000 tons biomass/day
Fuel gas production per plant	250 MMCF	34 MMCF
Number of plants required for 25% of current natural gas consumption	55	400 (400 facilities each consisting of about three 100 square mile energy farms)
Fraction of available remaining U.S. land area utilized (for 25% of present gas consumption)	Not applicable	Over 70% (i.e., over 70% of 95 million acres placed in aquatic biomass energy farms)
Maximum potential for fuel gas production (expressed as percent of nation's present natural gas consumption)	Very large	a) 35% (land-based aquatic biomass farming) b) 47% (open-ocean aquatic biomass farming)

1.3 Design Concepts and Engineering Analysis

The purpose of this project was to obtain costs for growing and harvesting aquatic biomass based on current scientific understanding. In order to obtain capital costs, operating costs, and finally, unit costs for harvesting the aquatic biomass, it was necessary to have suitable designs on which to base engineering and cost calculations. Early in the project it was recognized that two basic designs were required - one for the open ocean energy farm, the other for the land-based energy farm. With special features, each one of these two major designs were found to be suitable for near-shore and shore-line situations. To base engineering calculations and obtain costs, earlier work by Dr. Howard Wilcox of the U.S. Navy Undersea Center, San Diego, California was used for the open ocean system. For the land-based system Dynatech enlisted the support of CSO International, Inc. of Concord, California, a firm including Prof. Wm. Oswald, University of California, Berkeley as one of the founders and a firm active in design of large scale algae ponds. Thus, these two designs served to provide suitable background information on which to base both engineering calculations and costs.

In addition to design concepts or system "hardware" the site location was seen to be meaningful in the ascertaining of the maximum number of either land-based or open ocean systems that may be projected. To this end, careful review was given to available sunlight, current land usage, water availability (precipitation, evaporation, and percolation), cloud cover and other factors - these are included in a separate section on Site Locations.

Design options for many possible situations were considered and a separate section is devoted to this topic. The systematic approach to these design options was useful when investigating alternative aquatic biomass systems for both the open ocean and land-based systems. For example, the giant kelp has been used by Wilcox and workers in planning an open ocean energy farm. Through the investigation of all design options, it was recognized that Sargassum has some desirable features from an engineering basis. Likewise, rather than work with selected micro or macro algae in the land-based system, the delineation of all design criteria lead to the consideration of flowering plants (angiosperms) as perhaps having more engineering potential for land-based aquatic biomass energy farms than any algae.

With this substantial background, the engineering analysis, economics, and sensitivity was carried out and three separate sections are devoted to these topics. In addition, supportive calculations are given in appendices. Over-all, the goal was not to be exhaustive in engineering detail; the goal was to evaluate which system designs had engineering and economic potential to warrant further detailed analysis and investigation by the U.S. Department of Energy.

1.4 Other Considerations

While engineering and economic analyses were required for the two principal design concepts, namely, open ocean and land-based systems, it is evident that other considerations must be investigated. For example, the limitation of both open ocean and land space in the United States was shown earlier in this Introduction. Also, the close "competition" of coal gasification was shown. Other major features receiving special attention in this program were environmental and legal aspects. Special sections on both the environmental and the legal aspects of aquatic biomass farming are included in this report. Due to the apparent total absence of legal and environmental considerations with the open ocean system, and, in fact, the apparently more severe problems in these areas, the open ocean system perhaps received more attention. For both land and ocean farms the problems of fog and cloud cover generation by a 100 square mile aquatic biomass energy farm are very real environmental considerations. On the other hand, special legal questions must be answered with the open ocean farm - is it a navigational system?, will it obstruct shipping?, etc.

1.5 National Workshop

As a required part of the contract with the Department of Energy, a national workshop was held near the end of this program. The national workshop was held January 24-25, 1978 at Kresge Auditorium, Massachusetts Institute of Technology, under the auspices of the MIT Marine Industry Collegium. Approximately 175 people attended this two-day workshop. A copy of the final program, a list of attendees, and a copy of the completed Opportunity Brief submitted to attendees is given in Appendix A.

Section 2

CONSTRAINTS ON SITE SELECTION

The proposed farm for the cultivation of aquatic plants is to be sited somewhere within the United States. The only restriction is that it be at least 100 square miles in extent, although these hundred square miles need not be contiguous. The farm may be located on land, on the shore, in coastal waters, or at sea. An important part of the program is selection of a location to be recommended. In such a selection process a number of constraints must be kept in mind. Some of these constraints are common to all of the potential sites for these farms, but in others are unique to specific potential locations. The purpose of this review is to present a qualitative background of some constraints which must be borne in mind in making decisions about the placement of such farms.

Initially, some facts concerning the nature of the off-shore waters of the United States may be presented. For this purpose figures showing the contours of the ocean floor off the West Coast, within the Gulf, and off the East Coast are presented in the following pages. It is of interest to examine the extent of three regions in these off-shore areas of the United States. These regions are the waters within the 200 mile limit, the extent of the continental shelf, and the location of the 30 meter, or 17 fathom, line. The 200 mile limit recently applied to the fishing industry by the United States is presented as a logical choice for the extent to which "within the United States" may be defined. The degree to which the 200 mile or any other geographical limit must be regarded as providing legal barriers to sea farm establishment is discussed in Section 8 of this report. The extent of the continental shelf is a reasonable definition of the area within which bottom anchored farm systems will be practical. Beyond the edge of the continental shelf the waters drop off to abyssal depths and anchoring to the bottom becomes exorbitantly expensive. Operation in such deep waters will demand development of free floating, dynamically positioned farm concepts. The 30 meter depth defines a zone within which it may be reasonable to expect growth of seaweed which naturally anchors to the bottom. This limit is a maximum depth although some kelp may grow at greater depths. Many other species are limited to depths much shallower than 30 meters, but an appreciation of the extent of waters of less than 30 meters deep provides a delineation of a zone within which it may be practical to depend on natural bottom anchoring of plants.

In Figures 2.1 and 2.2 the extent of the continental shelf may be seen clearly. Shallow depths are quite limited on the West Coast. Within the Gulf of Mexico, on the other hand, there are substantial areas of continental shelf. This is especially notable off of the west coast of Florida. In contrast, the east coast of Florida has a narrow continental shelf. Off of New Jersey, New York, and the New England states, trending up to Nova Scotia, there are substantial areas of continental shelf. Figure 2.1 also shows a portion of the sea bottom off southern Alaska. It may be seen that substantial areas of continental shelf exist, but the quantity of solar radiation delivered to the waters off of Alaska is insufficient for mass algal production. Hawaii, on the other hand, represents our southern-most U.S. location and has the potential for high production because of favorable sunlight. However, as Figure 2.1 shows, the shelf off Hawaii is limited, and the waters plunge off to abyssal depths quite near shore.

The extent of the 200 mile limit is very simply defined off of the West Coast as shown in Figure 2.3. In Figure 2.4 it is seen that the shape of the 200 mile limit within the Gulf is somewhat convoluted, as we share the Gulf area with Mexico, and becomes constricted by the narrow straits between Florida and Cuba. Another constriction occurs between Florida and the Bahamas. Off the Atlantic coast, as Figure 2.5 indicates, the pattern is again uncomplicated until the area adjacent to Canada is encountered.

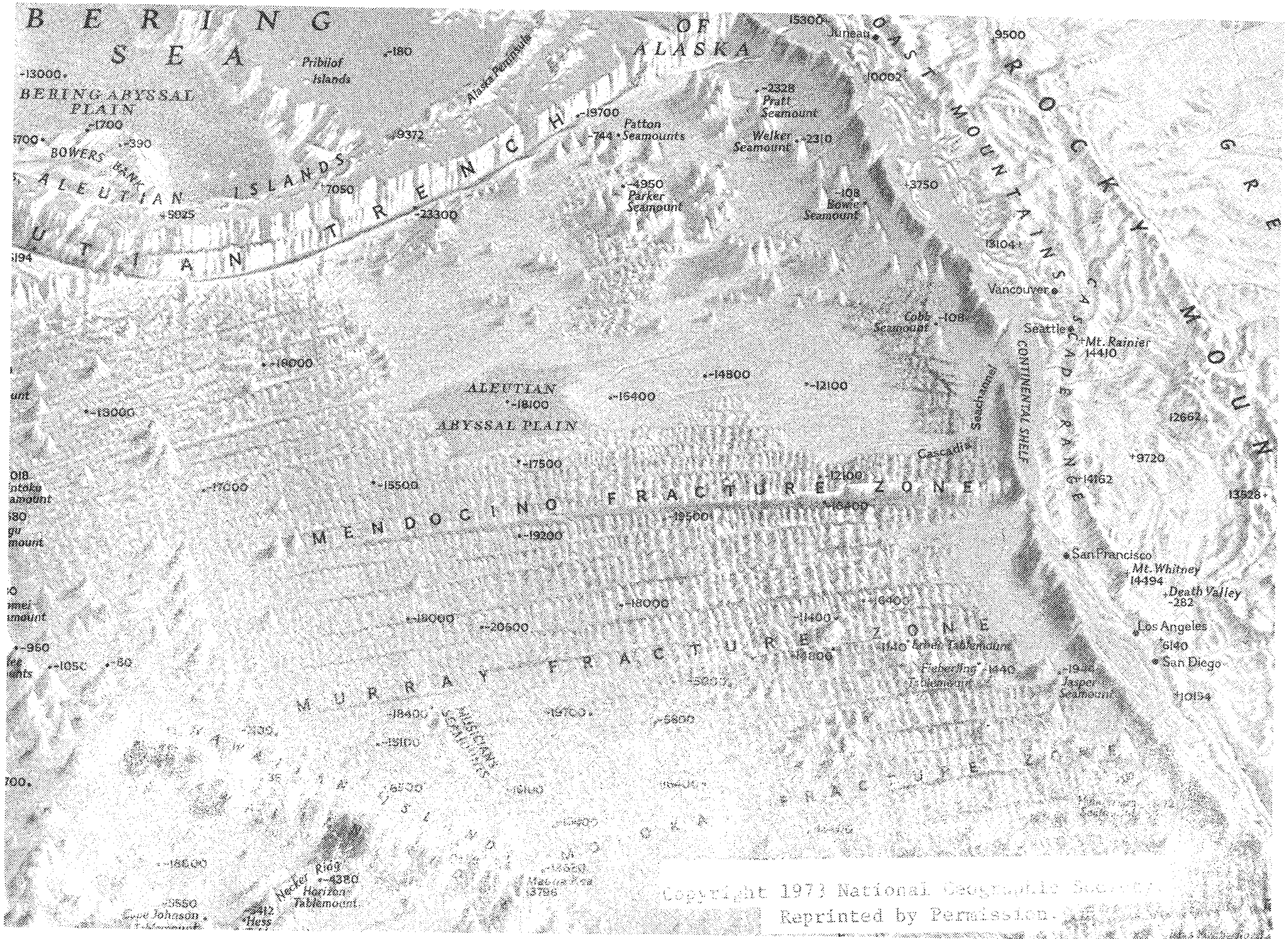


Figure 2.1

Contours of Pacific Ocean Floor

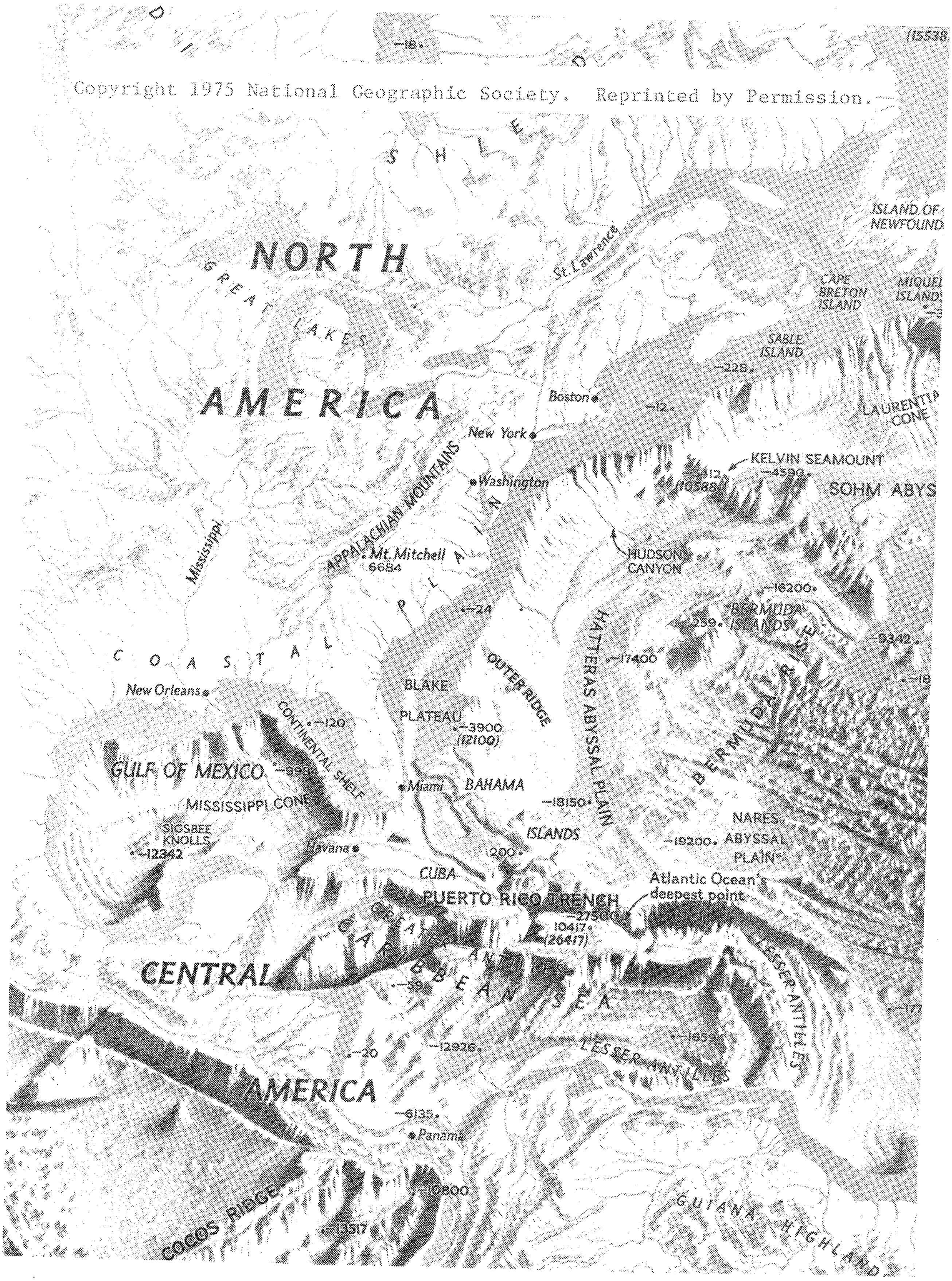


Figure 2.2

Contours of Gulf and Atlantic Ocean Floors

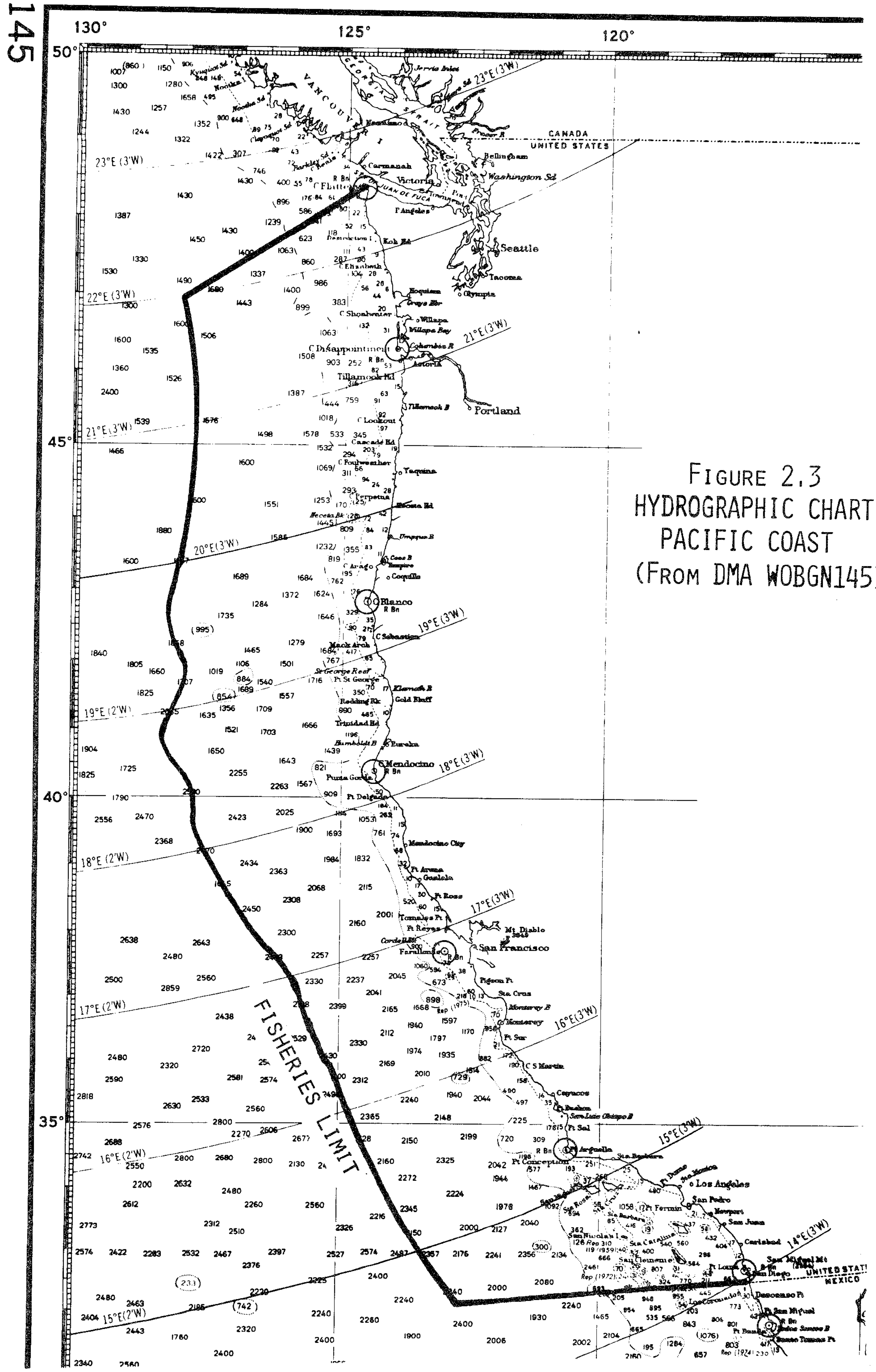


FIGURE 2.3
HYDROGRAPHIC CHART
PACIFIC COAST
(FROM DMA WOBGN145)

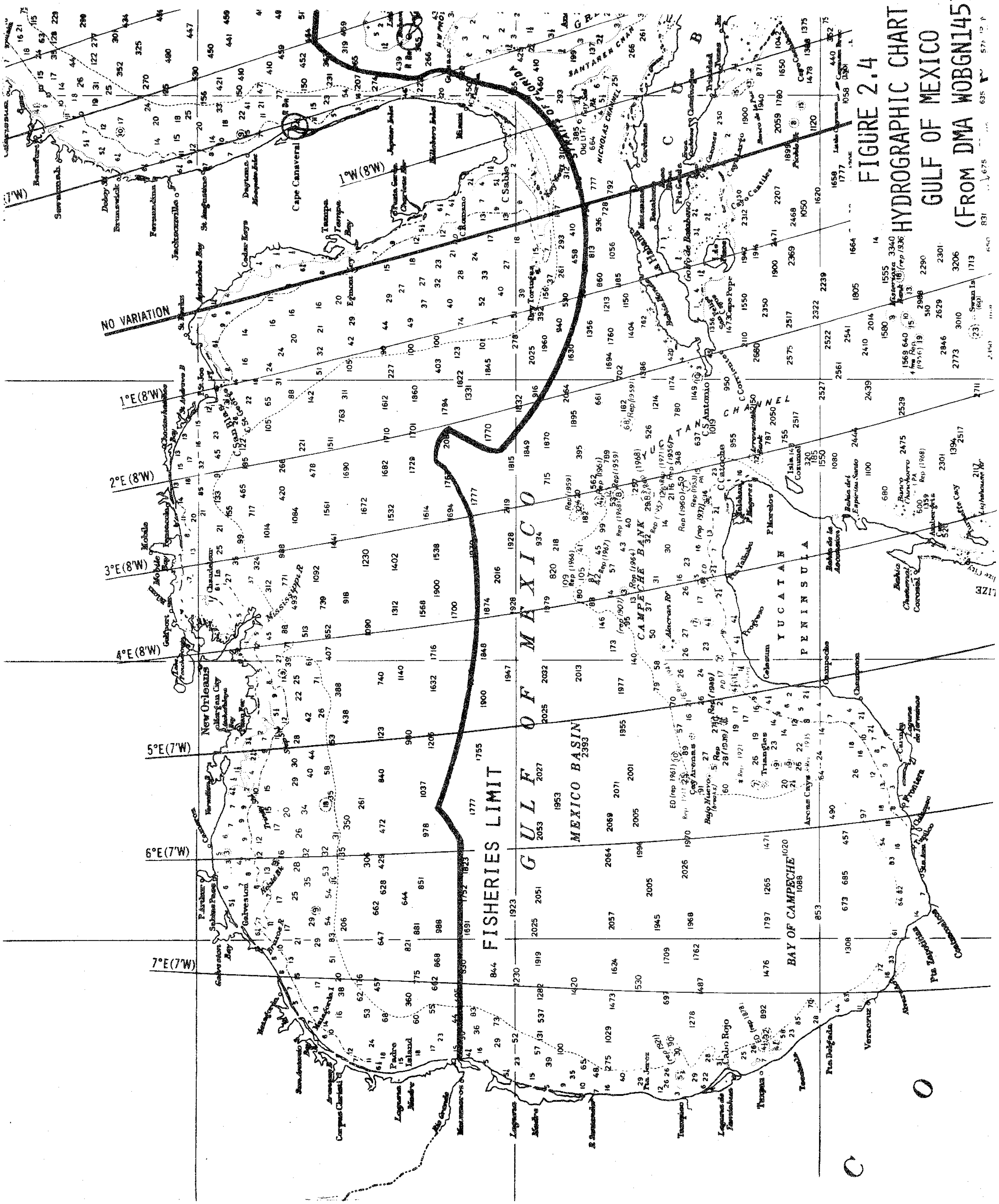


FIGURE 2.4 HYDROGRAPHIC CHART GULF OF MEXICO (FROM DMA WOBGN145)

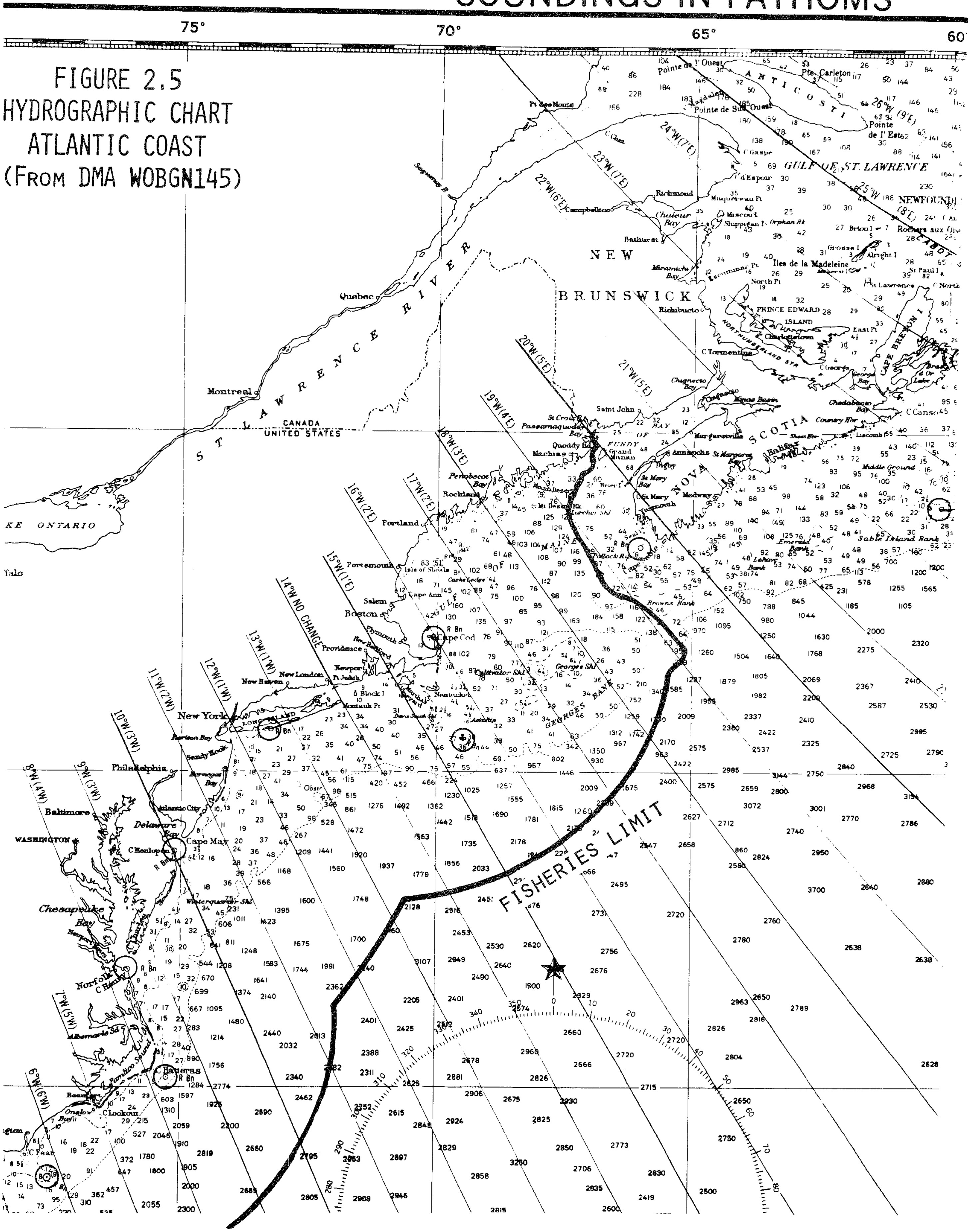


FIGURE 2.5
HYDROGRAPHIC CHART
ATLANTIC COAST
(From DMA WOBGN145)

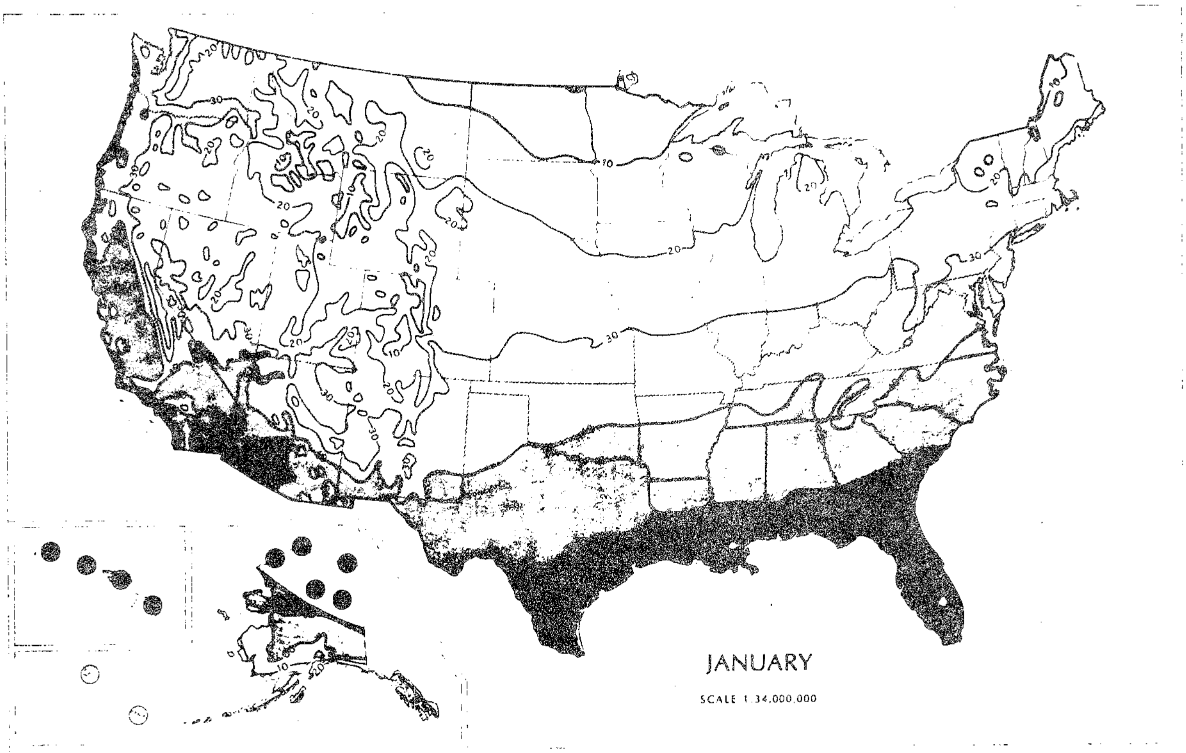
The locus of the 17 fathom line may also be determined from Figures 2.3-2.5. Clearly it virtually hugs the West Coast. There is a somewhat more generous area within the 17 fathom line off the New Jersey-Carolina shores. The greatest extent is within the Gulf, notably off the west coast of Florida.

The depth of water off our coast may be examined from another standpoint, namely, the depths from which nutrients may be drawn. In later sections of this report much discussion of the quantities of nitrogen and phosphorous available at various depths in the ocean will be given. In general, it is worth pointing out that relatively shallow waters are nutrient deficient, thus practical access to deeper waters containing nutrients is a requirement for any site under consideration.

The ambient temperature of an area under consideration may pose a limitation on the growth rate or season available for growth of plants. In the case of marine algae conditions both too warm and too cold may be of concern. Each plant species has an optimum temperature range at which high rates of growth are attained. Aquatic plants may be classified as cryophilic, mesophilic, or thermophilic depending on whether they thrive at low, medium or high temperatures. Within that range, increases in temperature increase growth rate until a critical point at which an increase in temperature either does not affect growth or decreases growth rate. Different strains of plants have been developed that can tolerate higher or lower temperatures. For instance, a strain of the giant kelp <u>Macrocystis</u> has been developed that can be grown in warm water.

In the case of land based systems cold weather may limit growth rate, or, in the extreme, freeze growing ponds. Such problems may be overcome in principle by "greenhouse" operations, but problems such as the blocking of light by condensation and the capital cost of such structures may rule out greenhouse protection. A judgement about the areas of the United States suited from the standpoint of ambient temperature to land-based plant growth may be made by reference to charts of monthly average temperature distribution. Such charts for the coldest months of the year, December and January, taken from the National Atlas, are reproduced in Figure 2.6. The temperature contours within the "lower 48" states on the charts for these two months range from 10° to 50°F. The regions within the 50°F contour (the areas appearing as black) are confined to the lowest tier of states. With the exception of the California coast and desert areas the 50°F contour lies below latitude 35°N during these months. Indeed, the 40°F contour is not much above that latitude, again, with the exception of the west coast. Accordingly, it may be seen from these charts alone that the area within which year round growth may be practiced is severely limited. If cultivation is to be practiced north of an area roughly defined by the 50°F contour in the coldest months, long periods of dormancy must be accepted, or the farms must be thermally protected in some way.

A further requirement is sufficient insolation. The sunshine received is another seasonally and location affected variable. The mean annual hours of sunshine over the United States varies by a factor of about two, i.e., from about 2000 to 4000 hours. In terms of hours of sunshine the southwestern states clearly lead. A better index is the integral of solar radiation. The variation in annual solar radiation in the United States is from 300 to 500 langleys. This index is more latitude dependent than days of sunshine, consequently the favored region in terms of solar radiation once again is the southern tier of states.



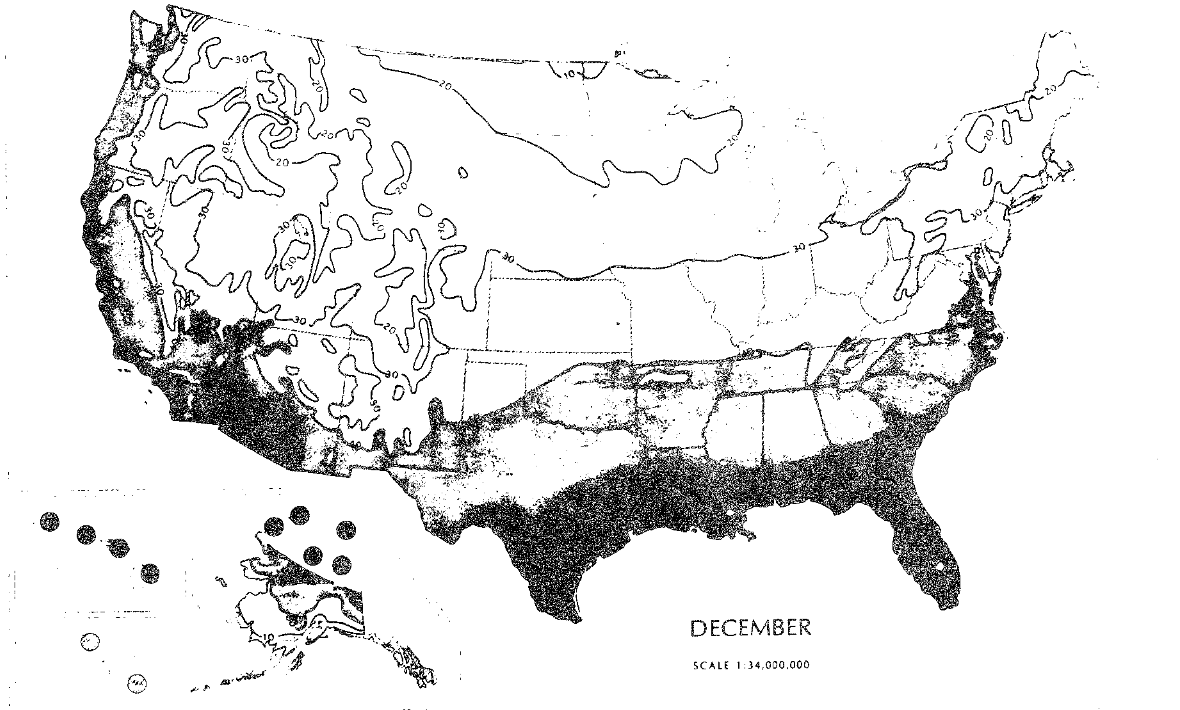


Figure 2.6

Mean Monthly Average Temperature

December & January

(From Sheet 106, National Atlas)

The most important issue facing the production of biomass from either terrestrial energy crops or land-based aquatic crops is the availability of land and water resources to be allocated to such an enterprise. If water could be made available at reasonable cost, land unsuited for productive use could be used for energy farms. Unfortunately, water is a relatively scarce resource in many parts of the United States, and its lack may restrict the use of such lands. Of the 2.3 billion acres of land in the U.S. (including Alaska), 78 percent or 1.8 billion acres are devoted to cropland, forestland, or grassland. In Figure 2.7 is depicted the major uses of land in the United States in 1969. Current estimates indicate no significant changes in land utilization.

Because of the intense utilization of other lands in the United States, the land resources necessary for production of any form of energy crop, terrestrial or aquatic, must necessarily be allocated from the existing categories of cropland, forestland, or grassland. Among the acreage of usable land (usable because of physical characteristics such as slope, fertility, and climatic factors) in these above categories, approximately 35 percent offers some economic and physical potential for biomass production.

A 1967 inventory and a complementary survey in 1975 by the U.S. Department of Agriculture revealed that of the total U.S. land area, 265 million additional acres of land (with and without limitations) could be considered as suitable for conversion to cultivation, as presented in Table 2.1. However, of this total, only a portion can be considered currently well adapted. Usage for cultivation will depend upon general water availability and/or public programs to provide irrigation water, drainage improvement, and soil conservation. It is unlikely that any lands in the medium or low potential categories, as listed in Table 2.1 would provide resources for biomass production. In many cases the cost of reclamation may be too great to make biomass production a profitable enterprise. Therefore, the

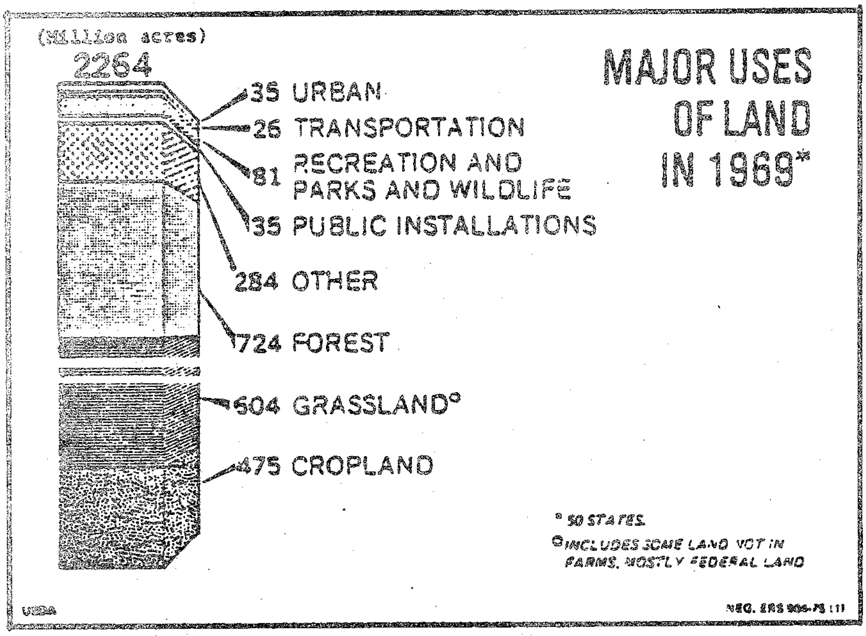


Figure 2.7

Major Uses of Land in 1969 (2)

Table 2.1

Potential for Conversion to Cropland(2)

(Million Acres)

Region	Potential: High, Short Run *	High, Long Run*	Medium, Short Run	Medium, Long Run*	Low†	Totals: Short and Long Run
1. Plains	48.1	4.1	-	-	2.6	54.8
2. North Central	15.3	13.8	-	-	7.7	36.8
3. Florida	1.3	2.9	-	-	-	4.2
4. Miss. Delta-Gulf Coast	3.5	6.7	-	-	0.8	11.0
5. Coastal Plain-Piedmont	-	-	18.2	19.8	27.3	65.3
6. Atlantic Coast Lowlands	-	-	1.3	7.4	0.5	9.2
7. Texas-Okla. Prairies	-	-	9.7	0.6	2.0	12.3
8. Appalachian-Ozark≠	-	-	-	-	24.9	24.9
9. Northeast-No. Great Lakes§	-	-	-	-	32.4	32.4
10. Rocky Mtn.-Far West**	-	-	-	-	13.6	13.6
Total	68.2	27.5	29.2	27.8	111.8	264.5

* Drainage necessary.

† Forest and other land with erosion problem. Regions 1 through 7.

≠ Fields small and scattered.

§ Short growing season.

** Water shortage.

remaining 95 million acres of high potential lands (short and long run) probably offer the greatest opportunity for energy farming - both terrestrial crops and land for construction of large aquatic biomass ponds.

The limited amount of area available for practical open-ocean farming of aquatic biomass may also be considered. It may be estimated that there are approximately 3000 miles (projected length) of United States coastline. If it may be practically assumed that open-ocean farming will be permitted up to the 200 mile commercial or economic zone, then it is seen that 600,000 square miles of available open-ocean space is contiguous to the United States. Since already much of this area is traversed with shipping lanes and used directly for fishing, it is clear that not all this area may be considered as being available for open-ocean farming due to other needs. Further, in both the Atlantic Ocean and Pacific Ocean off the northern one-half of the United States, insolation may limit open-ocean farming production to unattractive levels. In the broad terms being discussed here the area for open-ocean farming may be seen as comparable with the area available for land-based aquatic biomass farming.

Because of the importance of provision of the nutrients nitrogen and phosphorus in the mass cultivation of aquatic plants, it is of keen concern to determine whether natural upwelling in the ocean can be depended upon to deliver nutrients to the marine farm. The status of understanding of the phenomenon of natural upwelling, with respect to both mathematical modelling and observation, has been reviewed by Smith[3]. In the area of the coastal waters of the United States, of concern in this evaluation, the principal occurrence of upwelling is off the coasts of California, Oregon, and Washington. This is in keeping with the observation that the forces responsible for development of upwelling are exerted most strongly and reproducibly at the western coasts of the world's land masses. To a lesser extent more localized upwelling is observed periodically off the east coast of the United States.

Conditions are favorable for the development of natural upwelling off the west coast of the U.S. during the months of April-September. It is observed to occur initially in the southern reaches of the coast and to progress northward during this period. By October upwelling generally has ceased. During the favorable season, localized reversals are observed. These cessations may last for a few days or longer, and their impact on aquatic life is abrupt and profound, as fishermen frequently observe. The extent of the region to which upwelled water is delivered varies, but 10 km offshore is perhaps an average. The maximum extent is about 20 km (12 miles). The steepness of the continental shelf, as well as the presence of headlands and bays, appear to be factors which determine the distance of seaward extent of upwelling.

It has been argued that advantage should be taken of natural upwelling in choosing a site for an algal farm. If it were possible to avoid the cost of raising deep, nutrient-rich waters to an algal farm or the cost of provision of artificial nutrients, an important reduction in the cost of operation would be attained. Offsetting this advantage is the fact that dependence on natural upwelling will not permit continuous crop production. Intermittent production at uncertain periods must support the total capital cost of the farm operation and imposes periods of idleness on equipment, manpower, and the associated energy producing plant dependent on algal feed-stock. These disadvantages impose severe economic burdens on a process based on natural upwelling. As a general conclusion it may be stated that dependence on natural upwelling to provide total nutrient supply to a 100 square mile marine algal farm in U.S. waters is not practical. The contribution of natural upwelling to such an operation could be a welcome adjunct in some locations at some seasons, but a prudent designer cannot expect to depend on year round, total provision of nutrients through natural upwelling. The problem is perhaps put in best perspective by a quotation from the literature: "Although the upwelling regions seem well defined, the process itself has, as yet, no constant or dependable schedule of when it might arrive or how long it will last"[4].

Section 3

DESIGN CRITERIA

This section of the final report provides an outline of the cultivation systems analyzed for this study. The cultivation of all photosynthetic aquatic plants which contribute significant quantities of biomass in the natural environment were considered. These include marine macroalgae; marine angiosperms; freshwater angiosperms; and marine, brackish and freshwater microalgae.

The criteria used to develop the systems were based on information on mass cultivation and systems design currently available in the literature and from consultation with research scientists and engineers active in the field of plant cultivation. This background information was compiled in a topical report (5) prepared by Dynatech R/D Company in collaboration with Woods Hole Oceanographic Institution and it provides a detailed account of the biology of aquatic plants, factors affecting their productivity, yields attained to date, and cultivation techniques. The discussion of these topics is, therefore, only summarized here.

Of primary importance to the basic system design is the determination of biomass yield. Section 3.1 reviews the physical and biological factors which limit plant yields in mass cultivation. A yield was assumed for all systems based on theoretical models of organic production under optimum conditions and reported yields from the literature.

In general, all aquatic plants have the same basic physical requirements and biological limitations for growth. However, depending on the natural mode of existence of the plant and the location of the cultivation system (open ocean, coastal, shoreline, or inland) provision of those requirements is unique for each type of plant and each system. Therefore, in order to systematically evaluate the cultivation of each type of plant, a model system was designed which provides optimum conditions for growth. Each cultivation system, as outlined in a series of flow diagrams (Figures 3.1, 3.2, 3.12, 3.13, 3.17, 3.19, 3.20, 3.24) and discussed in Sections 3.2 - 3.5, consists of eight elements: support, containment, harvesting, positioning, water, mixing, nitrogen and carbon. The support element in all systems is responsible for stocking the farm initially and maintaining the standing crop, monitoring growth, and the density of the standing crop, protection of the crop from predation and disease, and control of undesirable species. The containment element includes methods to hold the plants within a defined area and the positioning element functions to control the movement of the containers. The harvesting element includes not only mechanical harvest of the plant material, but also transport to the processing location. Processing of the plant biomass, however, is not included in this study. The last four elements - water, mixing, nitrogen and carbon - are the key elements required to sustain growth. The water element functions to provide and distribute a growth media, and the mixing element provides adequate water exchange. The nitrogen and carbon elements provide a source of these nutrients and their distribution throughout the system.

A number of options are listed under each of the eight elements. For example, in Figure 3.1 there are three positioning options - fixed, dynamic, and natural. Each of these options was analyzed for viability based on engineering feasibility, environmental and political impact, and economic and energetic stability. When reading the flow diagrams from left to right, the omission of any option cancels every option further right. For example, if positioning by natural forces is eliminated, 3 of the 9 design systems represented in Figure 3.1 are eliminated. In many cases, the same options apply to several cultivation systems and these will be discussed in detail only when first introduced.

3.1 Factors Affecting Yield

Before a numerical value can be assigned to "yield" for the purpose of system modeling it is essential to have a clear understanding of the word and of its relationship to "growth" and "productivity". Although these three terms are often used interchangeably, when describing biomass output, they actually have distinctly different meanings.

Growth of organisms typically follows an exponential pattern in early life until a peak is reached and growth remains constant or decreases. For aquatic plants specific growth rate, defined as percent increase per unit time, averages about a 5% increase in weight per day under controlled conditions, but closer to 1% per day for natural populations. For the mass culture of aquatic plants the numerical magnitude of growth rate is not meaningful, unless culture density is known.

Productivity, the product of specific growth rate x density, is expressed as growth per unit time and area. Organic production is normally measured and reported in units of dry weight that include ash or non-volatile solids. Ash content is usually small, on the order of 10%, in most terrestrial and freshwater aquatic plants, but it represents as much as 50% of the dry weight of marine plants (Table 3.1). Consideration of plants as a biomass source for energy must take into account the ash content of the crop in evaluation of their reported yields.

Yield, the measure of material harvested, is expressed as biomass harvested per unit area per unit time. Conventionally, short-term yields are given as grams/meter squared/day and sustained large-scale yields as metric tons/hectare/year, both in units of total dry weight. It is the sustained large-scale yield which must be considered for an economic analysis of mass cultivation. The numerical value of productivity and yield are the same only if all organic matter produced is harvested. However, this is usually not the case in mass cultivation, since plant material is left unharvested to restock the culture.

3.1.1 Physical Requirements for Growth

Although different species of aquatic plants and sometimes even different strains of the same species, have varying tolerances and optimum conditions for growth, the basic requirements for growth of any photosynthetic

Table 3.1

AQUATIC PLANT COMPOSITION

Species	Dry wt % wet wt	Ash wt % dry wt	C-content % dry wt	N-content % dry wt	References
MARINE MACROALGAE					
Macrocystis pyrifera	14 - 18	34	20 - 31	0.7 - 3.8	(6), (7), (8), (9)
Nereocystis leutkeana	10	52		0.81 - 3.1	(8), (9)
Sargassum vulgare		16 - 25	1.23		(9)
Chondrus crispus	22	25 - 28		0.7 - 3	(9), (10)
Gracilaria verrucosa		10		1.5	(9)
MICROALGAE					
Microcystis aeruginosa		7 - 43		4 - 7	(9)
Nostoc communis		15		3 - 6.5	(9)
MARINE ANGIOSPERMS					
Thalassia testudinum	67 - 75	14		2.3	(11), (12)
Zostera marina	68	20	31 - 39	1.5 - 2.5	(9), (13)
FRESHWATER ANGIOSPERMS					
Eichhornia crassipes	5	15 - 26	18 - 40	.9 - 2.9	(14), (15), (16)

plant are the same: light and nutrients. The availability and utilization of light is affected by plant density and water temperature, while the availability of nutrients is controlled by water circulation.

In the photosynthetic process, carbon dioxide is reduced to organic matter by light energy. Photosynthesis increases with increasing light intensity in a linear relationship up to the point of saturation when the photosynthetic rate remains constant or decreases. The saturation intensity may be affected not only by photic energy, but also by thermal energy and it may vary with different plant species and the previous history of the plant.

The quantity of incident solar radiation reaching an aquatic plant is affected by the density of the standing crop. That is, at low densities plants are often unable to utilize all of the sunlight while at high densities, self-shading affects specific growth, the ratio photosynthesis to respiration becomes smaller, and net production or yield decreases. Hence, production or yield as a function of plant density is described by a bell-shaped curve. To maintain high productivity, it is desirable to monitor crop density and to harvest the culture in order to maintain the optimum density.

Photosynthetic efficiencies are also affected by temperature. Each plant has an optimal temperature range at which high rates of growth are attained. Within that range, increases in temperature increase growth rate until a critical point at which an increase in temperature either does not affect growth or decreases growth rates.

Ryther (17) has determined that considering the mean daily total incident radiation reaching an aquatic plant and a 2% conversion efficiency, the maximum potential production of organic matter within the latitudes of the continental United States is less than 80 m tons ash free dry wt/ha/yr. This maximum potential yield agrees favorably with reported yields from large-scale operations for both microalgae and macrophytes (Table 3.2).

Plant yields from short-term small-scale experiments, however, (Table 3.3) are often reported as high as 10 times those of long-term studies, suggesting that a conversion efficiency higher than 2% can be attained over short periods. The low, more realistic, photosynthetic efficiencies in long-term studies may be explained by the inability to provide ideal conditions, such as adequate nutrient absorption and control of epiphytes, grazers, and disease.

Nutrients in a form utilizable by the plant are also required to produce organic matter. As discussed in the Topical Report (5), there are numerous nutrients and micronutrients required for growth, but for our purposes, nitrogen and carbon were considered to be the most important nutrients, since both are required in large quantities (Table 3.1) to obtain high growth rates and both are sometimes growth limiting. Nitrogen in the form of nitrate is the element most often limiting plant growth in the marine environment and carbon is often limiting in freshwater systems. The carbon concentration in seawater is usually relatively high, about 25 mg/l, and may contribute as much as 20 - 40% of the dry weight in marine plants (Table 3.1). Although the situation is not yet clear, carbon may be growth limiting in mass culture marine systems when other nutrients are in abundant supply.

Many freshwater macrophytes absorb carbon dioxide directly from the atmosphere where it is readily available, but marine macrophytes and most microalgae require water movement to enhance CO_2 transport from the atmosphere. Mixing is also essential to seaweed and microalgal cultures to disperse nutrients, which are absorbed across all plant surfaces directly from the water, so that plant surfaces come in contact with them and so that diffusion gradients of nutrients at the cell surfaces are broken down. Marine seagrasses, however, and rooted freshwater macrophytes remove nutrients with their roots from the soil like terrestrial plants. These plants grow well in areas of slow water movement, since nutrients drop out of suspension and concentrate in the bottom substrate.

Table 3.2

LARGE-SCALE OPERATIONS ($\geq$ 0.4 ha)

A. Harvested Yields from Large-Scale Cultivation and Natural Populations

Genus	Location	Type of System [a]	Duration Days	Average Yield g total dry wt per m^2 per day	Ref.	Theoretical Annual Yield ton total dry wt per acre per year	Theoretical Annual Yield m ton total dry wt per hectare per year
MICROALGAE							
Spirulina	Mexico City, Mexico	L (200,000 m^2 total size)	?	10	18	16.2	36.5
Chlorella	Japan	L (11,500 m^2 total size)	365	21	19	34.0	76.7
Chlorella	Taiwan	L (16,200 m^2 total size)	365	22	19	35.6	80.3
MACROALGAE							
Eucheuma	Philippines	N	365	9.86	20	16.0	36
Laminaria	Nova Scotia	N	365	13.15	21	21.3	48
Laminaria	China	N	365	4.10	22	6.6	15
Macrocystis	California	N	365	1.46[b]	23	2.4[b]	5.3[b]
Macrocystis	California	N	?	0.6	24	1.0	2.2
Eucheuma	Philippines	C	365	3.64	25	5.8	13
Gelidium	Japan	C	730	0.55[b]	26	0.9*[b]	1.5*[b]
Gracilaria	Taiwan	C	∿ 240	2.74	27	4.4*	10*
Porphyra	Japan	C	150	0.51	28	0.8*	1.9*
Porphyra	Japan	C	150	1.0 - 1.75[b]	26	1.6 - 2.9*[b]	3.7 - 6.4*[b]
Undaria	Japan	C	150	3.2	29	5.2*	11.7*
MARINE ANGIOSPERMS							
Thalassia	Florida	N	365	0.92 - 4.40	31	1.5 - 7.1	3.4 - 16.1

* This value does not reflect the true annual productivity, since the duration of the study was less than one year. Calculation of the value is intended for comparison only.

[a] Key: L - land based system; N - natural population in coastal waters; C - cultivation in coastal waters.

[b] Original data converted to total dry weight assuming dry wt = 0.20 x wet wt.

Table 3.2

LARGE-SCALE OPERATIONS ($\geq$ 0.4 ha)

B. Productivity of Natural Populations

Genus	Location	Type of System [a]	Productivity $gC/m^2/day$	Reference	Theoretical Productivity [b]		
					g total dry wt per m^2 per day	ton total dry wt per acre per year	m ton total dry wt per hectare per year
MARINE ANGIOSPERMS							
Halodule	North Carolina	N	0.48 - 2.0	32	1.4 - 5.7	2 - 9*	5 - 21*
Posidonia	Malta	N	2 - 5	33	5.7 - 14.3	9 - 23*	19 - 52*
Thalassia	Cuba	N	9.3 - 12.5	34	26.6 - 35	43 - 58*	97 - 130*
Thalassia	Puerto Rico	N	2.4 - 4.5	35	6.9 - 12.8	12 - 21*	25 - 47*
Thalassia	Florida	N	5.7 - 16	36	16.3 - 41.7	27 - 75*	60 - 152*
Thalassia	Florida	N	0.35 - 1.14	37	1.0 - 3.3	2 - 5*	4 - 12*
Thalassia	Florida	N	0.9 - 2.5	38	2.6 - 7.1	4 - 12*	9 - 26*
Thalassia	Florida	N	2.8 - 14	39	8.0 - 40	13 - 65*	29 - 146*
Thalassia	Bahamas	N	0.5 - 3	40	1.43 - 8.57	2 - 14*	5 - 31*
Zostera	Puget Sound	N	1.59	41	4.54	7*	17*
Zostera	Massachusetts	N	0.16	42	0.46	0.8*	2*
Zostera	North Carolina	N	0.93	32	2.66	4*	10*

* This value does not reflect the true annual productivity, since the duration of the study was less than one year. Calculation of the value is intended for comparison only.

[a] Key: N - natural population in coastal waters.

[b] g $C/m^2/day$ converted to g total dry $wt/m^2/day$ assuming C = 0.35 x dry wt.

Table 3.3

SMALL-SCALE OPERATIONS

Genus	Location	Type of System[a]	Duration Days	Production[b] g total dry wt per m^2 per day	Ref.	Theoretical Production ton total dry wt per acre per year	Theoretical Production m ton total dry wt per hectare per year
MICROALGAE							
Chlorella	Cambridge, Massaschusetts	L (56 m^2/unit)	52	2	43	3.3 *	7.3 *
Chlorella	Essen, Germany	L (6 m^2/unit)	∿ 30	4	44	6.5 *	14.6 *
Chlorella	Tokyo, Japan	L (15 m^2/unit)	10	3.5	45	5.7 *	12.8 *
Chlorella	Tokyo, Japan	L (13.8 m^2 total)	27	16	46	26.0 *	58.4 *
Chlorella	Jerusalem, Israel	L (4 m^2/unit)	35	12	47	19.6 *	43.8 *
Chlorella	Jerusalem, Israel	L (300 m^2/unit)	30	27[c]	48	44.0 *[c]	98.5 *[c]
Chlorella, Scenedesmus	Tokyo, Japan	L (147.8 m^2 total)	365	8.6	49	14.0	31.4
Scenedesmus	Dortmund, Germany	L (320 m^2 total)	?	10	50	16.3 *	36.5 *
Scenedesmus	Trebon, Czechoslovakia	L (12 m^2/unit)	?	15	51	24.5 *	54.8 *
Scenedesmus	Trebon, Czechoslovakia	L (50 m^2/unit)	65	16	52	26.0 *	58.4 *
Scenedesmus	Trebon, Czechoslovakia	L (900 m^2/unit)	89	12	52	19.6 *	43.8 *
Scenedesmus	Tylicz, Poland	L (50 m^2/unit)	71	12	52	19.6 *	43.8 *
Scenedesmus	Rupite, Romania	L (50 m^2/unit)	62	23	52	37.5 *	84.0 *
Scenedesmus	Firebaugh, California	L (1000 m^2/unit)	70	10	53	16.3 *	36.5 *
Scenedesmus	Bangkok, Thailand	L	?	13.4	54	21.8 *	48.9 *
Scenedesmus	Bangkok, Thailand	L (609 m^2 total)	?	15	50	24.5 *	54.8 *
Tolypothrix	Tokyo, Japan	L (5 m^2/unit)	?	6.4	55	10.4 *	23.4 *
Phaeodactylum	Plymouth, England	L (15.6 m^2 total)	?	∿ 10	56	16.3 *	36.5 *
Spirulina	Bangkok, Thailand	L (609 m^2 total)	?	15	50	24.5 *	54.8 *
Green Algae	Haifa, Israel	L (270 m^2 total)	365	15	57	24.5	54.8 *
Diatoms	Woods Hole, Massachusetts	L (1,080 m^2 total)	7	10 (max)	58	16.3 *	36.5 *
Diatoms	Woods Hole, Massachusetts	L (8 m^2 total)	15	13 (max)	59	21.2 *	47.4 *
Diatoms	Fort Pierce, Florida	L (15 m^2 total)	15	25 (max)	59	40.8 *	91.3 *
Micractinium	Richmond, California	L (48 m^2 total)	30	32 (max)	60	52.2 *	116.8 *
Micractinium	Richmond, California	L (2700 m^2/unit)	31	11.7 (max)	60	19.2 *	42.7 *
Micractinium	Richmond, Colifornia	L (12 m^2 total)	125	12.7 (max)	61	20.7 *	46.4 *
MARINE MACROALGAE							
Gracilaria	Fort Pierce, Florida	L	365	35.0	62	57.1	127.8
Gracilaria	Fort Pierce, Florida	L	365	20.0	63	32.6	73
Gracilaria	Fort Pierce, Florida	L	150	16.9	62	27.5 *	61.7 *
Gracilaria	Woods Hole, Massachusetts	L	166	16.9	64	27.5 *	61.7 *
Hypnea	Fort Pierce, Florida	L	150	17.6	62	28.7 *	64.2 *
Neoagardhiella	Woods Hole, Massachusetts	L	166	27.7	64	45.2 *	101.1 *
FRESHWATER ANGIOSPERMS							
Eichhornia	Fort Pierce, Florida	L	73	18.4	66	30.0 *	67.2 *
Eichhornia	Fort Lauderdale, Florida	L	7	13.8 (max)	67	22.5 *	50.4 *
Lemna	Fort Pierce, Florida	L	73	4.3	66	7.0 *	15.7 *
Lemna	Fort Lauderdale, Florida	L	7	∿ 4	68	6.5 *	14.6 *

* This value does not reflect the true annual yield, since the duration of the study was less than one year.

[a] L - land-based system.

[b] Average production unless indicated otherwise.

[c] Included non-algal solids from wastewater.

3.1.2 Biological Parameters Affecting Productivity

Biological parameters which affect productivity significantly, include encrustations, grazing, competition with other plants, pathogens, and senescence. A wide variety of plants and animals form encrustations on the surfaces of aquatic plants. These epiphytes usually do not harm the plant physically, but since they block out light, they are detrimental to plant growth. Plant surfaces may be harmed by organisms that feed on the epiphytes and incidently tear plant tissue and by herbivores which feed directly on the plant. Excessive grazing can be a serious problem and if not controlled, will completely destroy cultured aquatic plants.

Plants are constantly competing for space, light and nutrients with other plants of the same species and of different species. Both micro-algal and macrophyte culture have problems with phytoplankton blooms which may in a short time completely replace young stages of macrophyte cultures and all stages of microalgal cultures if not checked frequently. In biomass production, contamination by competing macrophytes may be particularly detrimental if the desired species, which may have been genetically isolated, has a much higher potential to produce energy than the competing species or strain of the same species. For instance, if the efficiency of an anaerobic digestion process to produce methane is at a peak when the substrate is 50% ash-free dry weight, introduction of competing species with a higher or lower dry weight may decrease the efficiency of the process.

Pathogens, such as viruses, bacteria, fungi and parasitic algae may have profound effects on the productivity of aquatic plants and may even eliminate the desired species completely. All of these biological parameters are best controlled by providing optimal conditions for growth of the desired species, since under stress conditions, such as an increase in water temperature or culture density, or a decrease in nutrients, plants are more susceptible to biological disturbances. Even under controlled conditions, however, some aquatic plants periodically stop growing vegetatively and enter a condition of senescence, which is unpredictable and unexplainable. This occurrence is particularly important, because until an explanation is found, there is no means of control and complete cultures will suddenly disintegrate.

3.2 Cultivation of Marine Macroalgae

Macroalgae or seaweeds occur in coastal marine waters usually at depths of 10 meters or less, but occasionally they may occur at depths of as much as 100 meters. Although they may be microscopic during early stages in their life cycles, the adult sporophyte plant is always macroscopic ranging from a few centimeters to 150 meters in length.

Seaweeds reproduce asexually, sexually, or by means of a complicated alternation between sexual and asexual generations. Asexual reproduction is merely vegetative growth of the adult plant. Sexual reproduction involves production of microscopic gametes which join to form a zygote, eventually developing into the adult. Although the adult plant may not require attachment to a hard substrate to survive, most species which reproduce sexually, require attachment for the early stages. Experimentation has led to the development of strains of seaweeds which, when held in suspended culture, omit the sexual stage and reproduce vegetatively only. In the natural environment, this phenomenon is exhibited by macroalgae which float on the water surface of the continuously circulating Sargasso Sea. Marine macroalgae have, therefore, been divided into three groups for this report, depending upon the mode of existence. They were either considered as being attached to a substrate, floating on the water surface, or suspended in the water. The first two of these groups may be cultivated in the open ocean, coastal and shoreline systems, but the third is restricted to a shoreline system.

3.2.1 Cultivation of Attached Marine Macroalgae

The majority of the marine macroalgae, including *Macrocystis*, *Gracilaria*, *Porphyra*, and *Chondrus* can be cultivated by attachment to an artificial substrate. In the open ocean (Figure 3.1) and coastal systems (Figure 3.2) these seaweeds are contained by attachment of the holdfast to

Figure 3.1

OPEN OCEAN SYSTEM

CULTIVATION OF MARINE MACROALGAE ATTACHED TO AN ARTIFICIAL SUBSTRATE

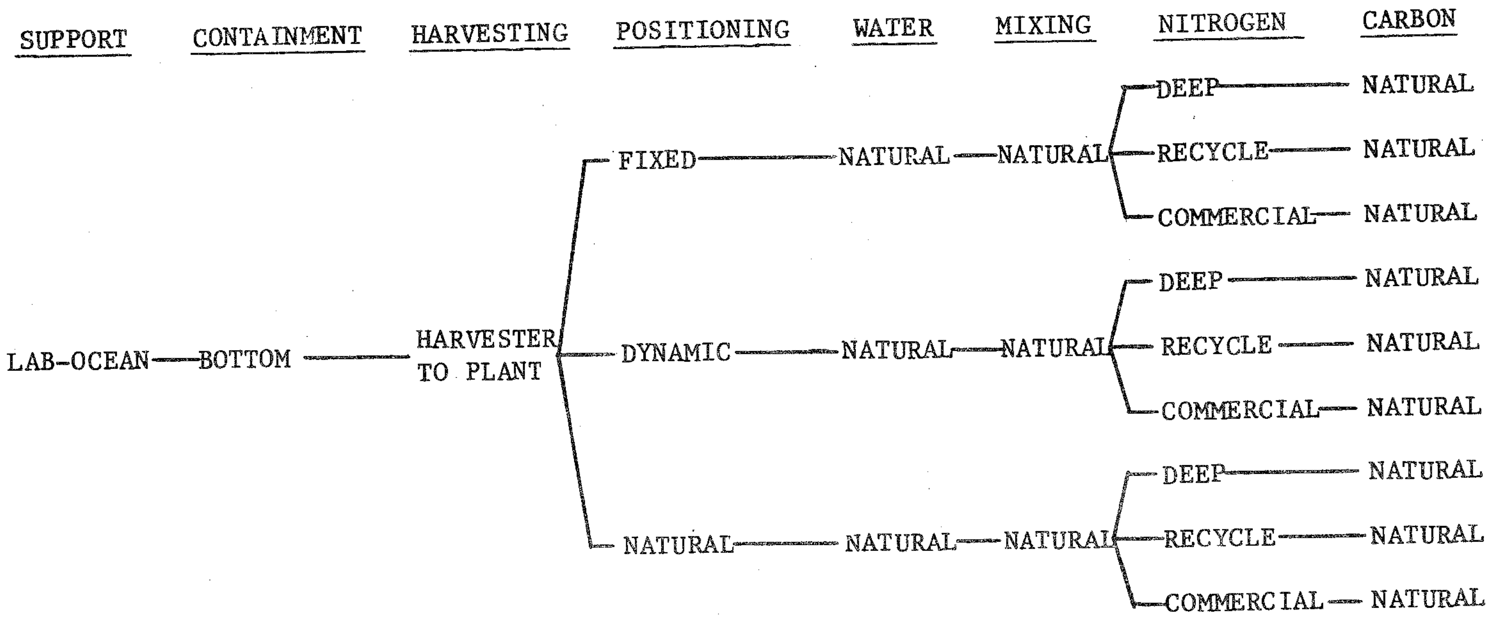
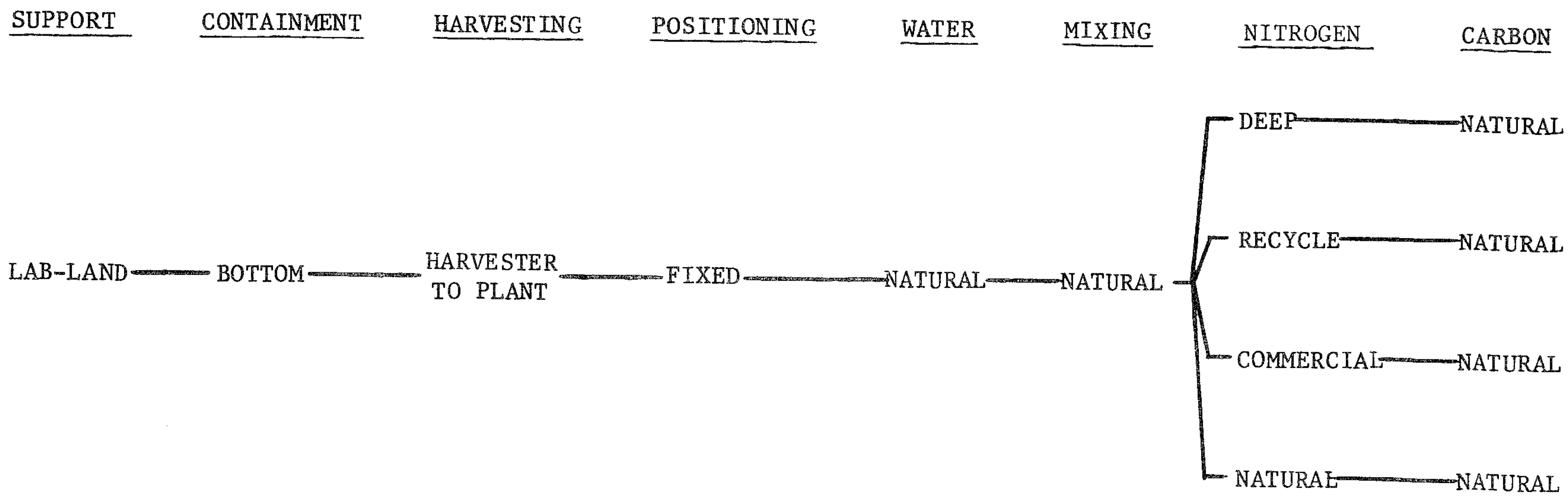


Figure 3.2

COASTAL SYSTEM

CULTIVATION OF MARINE MACROALGAE ATTACHED TO AN ARTIFICIAL SUBSTRATE



a network of lines, denoted by "bottom" containment. The initial attachment of these plants (support element) requires submerging the lines into seawater containing spores released from the adult sporophyte. This process is highly successful when performed under controlled conditions in the laboratory. Although adult plants can be transplanted directly from natural coastal beds, it is unlikely that the number of suitable plants from natural populations would be sufficient to stock 100 square mile farms without additional artificial seeding. Laboratory facilities and personnel for the support element can be land-based when the farm is located in coastal waters (Figure 3.2), but would need to be stationed on the site of an open ocean system (Figure 3.1).

A farm positioned in shallow coastal waters may simply be fixed to the sea floor by use of anchors (Figure 3.2), as diagrammatically represented in Figure 3.3. Although oil rigs have been tethered in water as deep as 4000 meters, the dynamics of holding the hardware and plants of a 100 square mile farm in place may require less rigid confinement. A ship can be held on the surface in a relatively fixed position with respect to the ocean floor without the use of anchors by a methodology termed "dynamic positioning". As illustrated in Figure 3.4, by regulating the amount of thrust and rotation of propellers on the fore, aft, and sides of a vessel, the motion of a ship can be controlled in any direction. Theoretically, the orientation and position of a farm can be controlled in the same manner by regulating the thrust of propulsers on the perimeter of the farm (Figure 3.5). The propulsers, represented in the drawing by barges, can be any buoyed structure, perhaps even a laboratory, equipped with thrusters of equal size at opposing sides to keep the system in tension and counteract forces induced on the farm due to current, wind and wave action. The third positioning option, "natural" (Figure 3.1) refers to a free-floating farm. In this case the farm may be positioned without mechanical devices, within a well-defined current system. As illustrated in Figure 3.6, major current systems in the Atlantic and Pacific Oceans and in the Gulf of Mexico follow circular patterns. A free-floating farm utilizes this environmental energy by moving with the currents. Harvest and maintenance periods may be timed to coincide with the movement of the farm over a particular point, but due to the lack of control of a free-floating system, the farm would

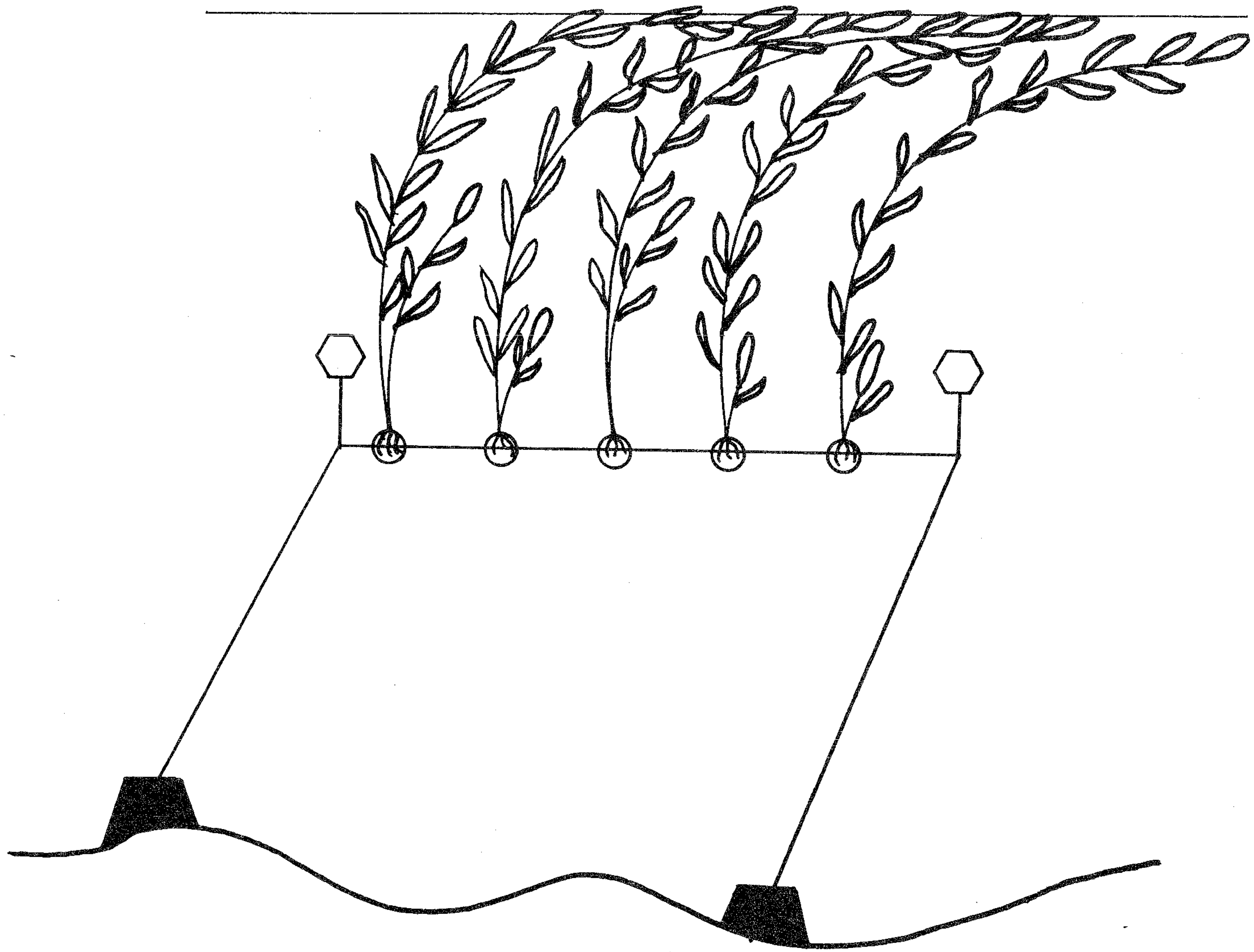


Figure 3.3

Diagrammatic representation of fixed positioning. The tethered substrate is held in place by anchors and buoyed upward in the water column. Plants are attached by the holdfast to the substrate.

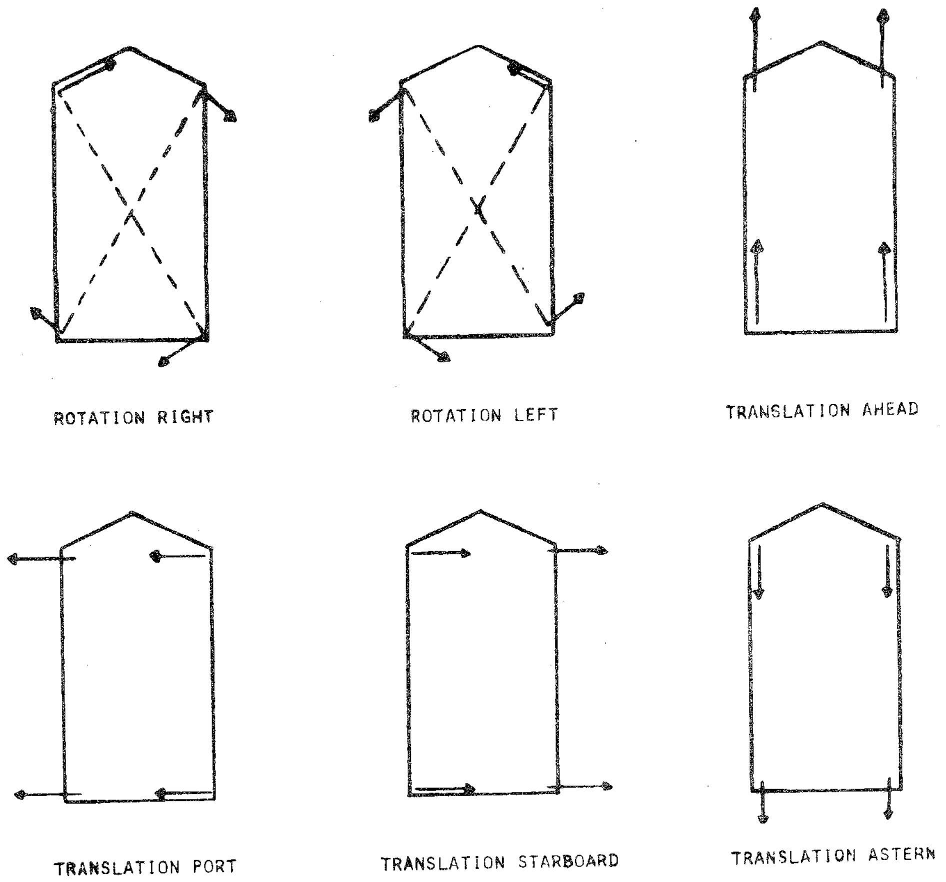


Figure 3.4

Diagram illustrating dynamic positioning of a vessel. The arrows represent the thrust of propulsion units.

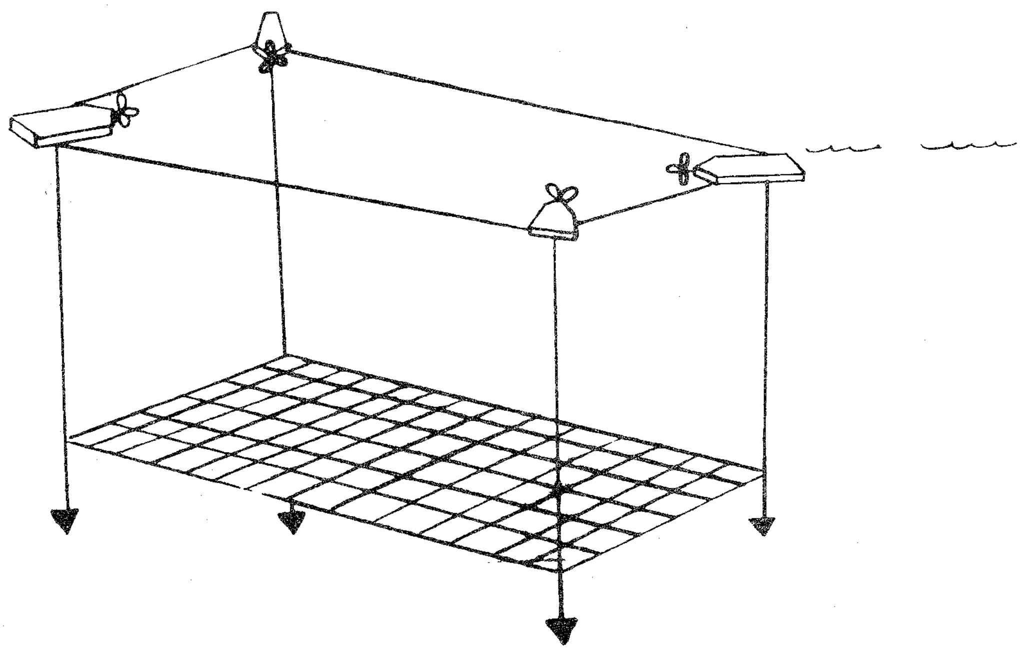


Figure 3.5

Diagrammatic representation of dynamic positioning of a submerged substrate. The substrate is held in tension by weights below and buoys above. The buoys are represented by barges which also function as propulsions.

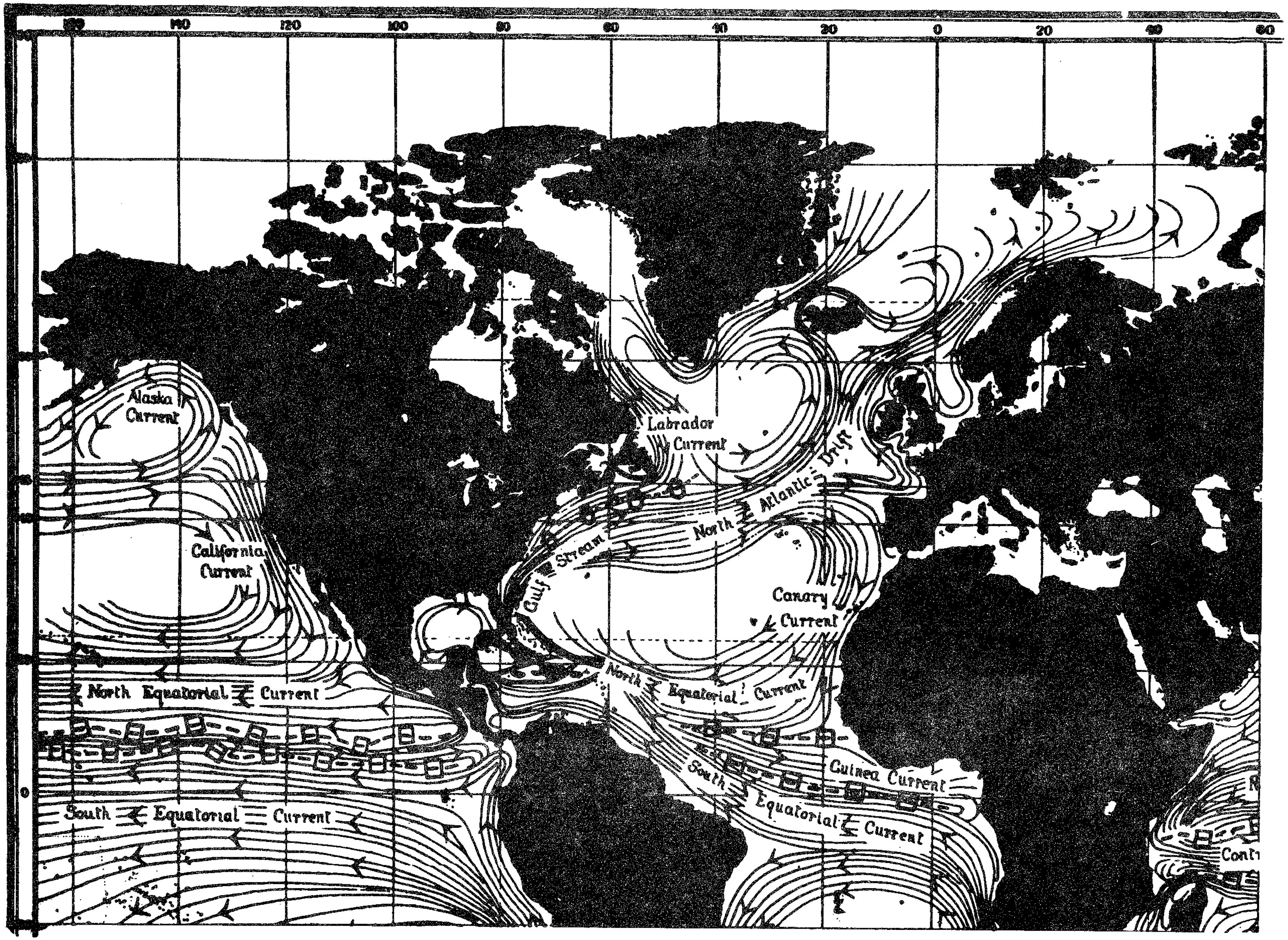


Figure 3.6

Major surface currents in the Atlantic and Pacific Oceans around the continental United States showing the main convergences. (69)

- - ⊟ - - ⊟ - - Tropical Convergence Zones

- - ⊖ - - ⊖ - - Sub-polar Convergence Zones

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be subject to changes in weather and similar environmental conditions. Besides the high risk of natural positioning, political interactions may be encountered if the farm drifts outside of U.S. waters.

The mechanical ease of harvesting attached marine macroalgae is determined primarily by the depth of the substrate, and hence, by the length of the adult sporophyte plant. It is an advantage to cultivate plants which attach to a deep substrate, so that allowance is made for the draught of the harvesting vessel. It is also easier to avoid entanglement with the substrate by harvesting the top portion of the plant rather than the entire organism. The giant kelp Macrocystis and other large attached seaweeds can be severed at the top without damaging the rest of the plant. Although most seaweeds are less than 1 meter long and must be attached immediately below the surface, Macrocystis can be grown on a substrate as deep as 30 meters. The fronds, which are at various stages in their life cycle, extend from the holdfast upward and spread over the surface (Figure 3.7). A harvester moving over the kelp forest cuts those fronds which are on or near the surface. If the terminal blade at the end of a frond is severed, that frond will degenerate and eventually drop off, but remaining terminal blades will continue to grow. Fronds of the giant kelp usually live 3 - 6 months and are then lost from the system. The harvesting vessels used currently in the kelp beds off the coast of California harvest plant material in the upper 1 - 2 meters. Moving backwards, the vessel cuts the plant and conveys the harvested material aboard via moving belts (Figure 3.8).

The supply of sea water is naturally sufficient in the open ocean and in coastal waters. In coastal areas, except in enclosed embayments, adequate mixing of the water is generated by tides, currents, and waves, while in the open ocean mixing due to wave action is most significant. Since the concentration of carbon in seawater is about 25 mg/1, the continuous renewal of sea water usually provides adequate quantities of carbon from the natural environment for the photosynthetic process.

As mentioned previously in Section 3.1.1, nitrogen is the element most often limiting the growth of marine plants. In the open ocean the concentration of nitrogen, utilizable by macrophytes, is not high enough to

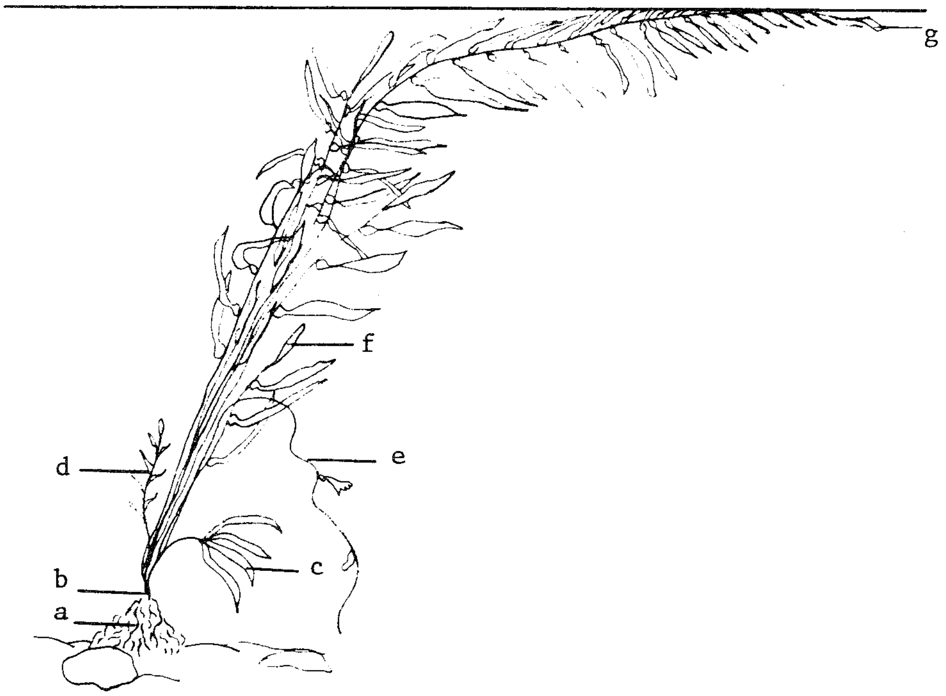


Figure 3.7

Diagrammatic representation of the attached marine macrophyte, Macrocystis.

a) holdfast

b) primary stipe

c) sporophylls

d) developing young frond

e) deteriorating senile frond

f) terminal blade, or growing point of young frond

g) terminal blade of mature frond in the canopy

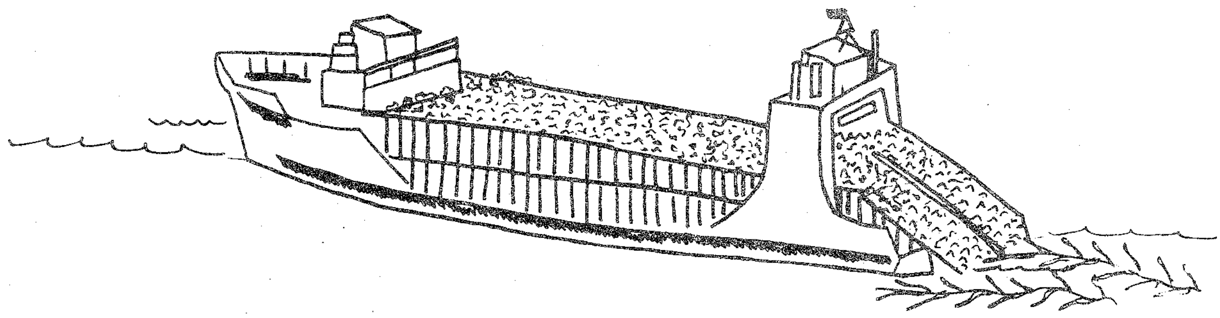


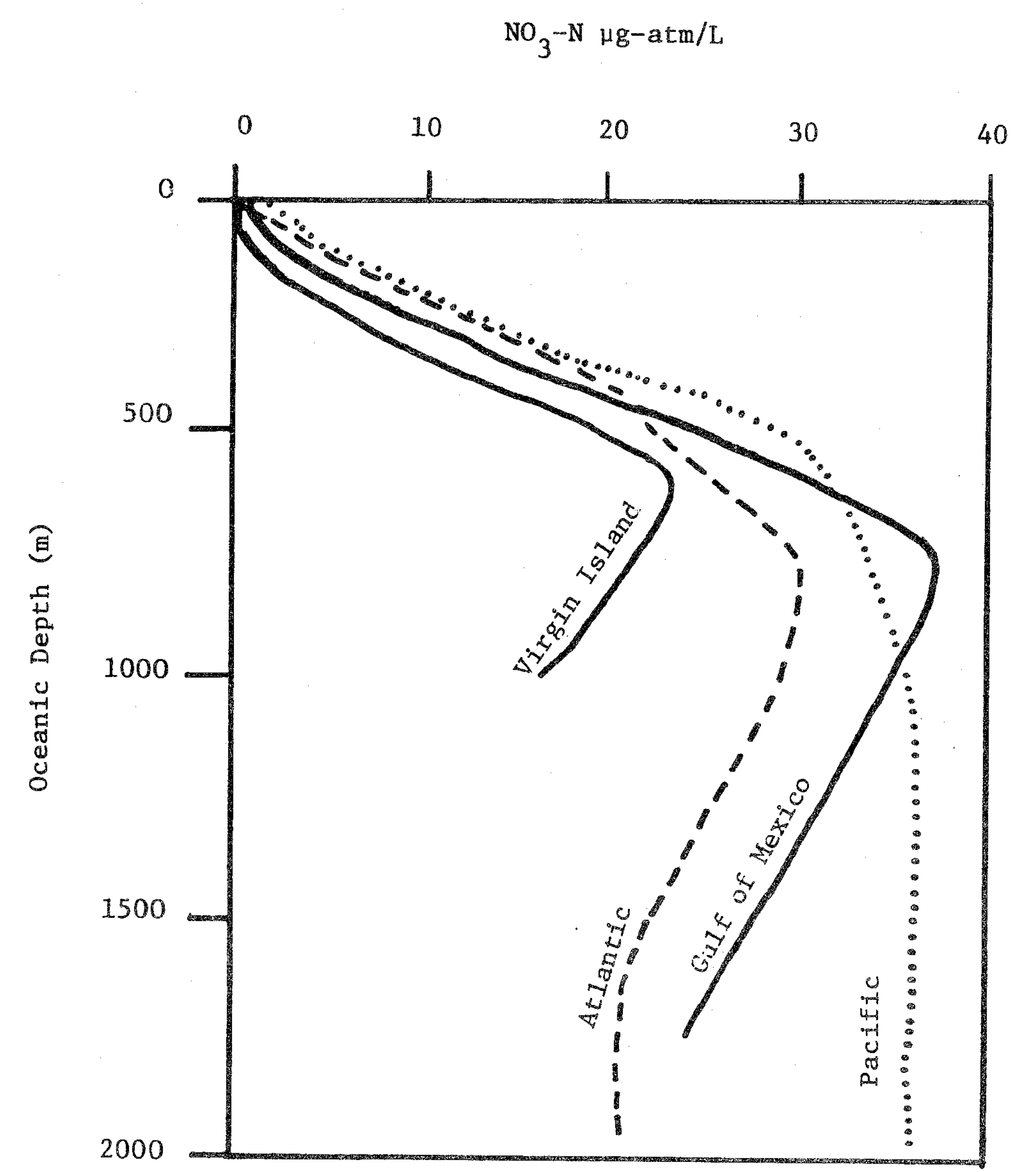
Figure 3.8

Diagrammatic representation of a ship used currently off the coast of California for harvesting the giant kelp, Macrocystis. The harvester moves backwards over the kelp canopy cutting at a depth of 1 - 2 m and hauling the seaweed aboard via conveyor belts.

sustain growth. Concentrations of nitrates, nitrites, and ammonia are often about 3 μg-atms/l in coastal waters, due to natural upwellings, organic disposal, tile drainage and agricultural run-off. Although nitrogen supplement may be required periodically, this concentration is high enough to sustain good growth and is, therefore, described as a "natural" nitrogen source option in Figure 3.2. Three other nitrogen sources were considered as potential supplies to fertilize the farm. They include deep seawater, recycled sludge from the digestion process, and other commercial sources. Although the concentration of nitrate-nitrogen in surface waters in the open ocean is too low to support high growth rates, the concentration increases dramatically with oceanic depth up to a maximum at about 600 -1000 m (Figure 3.9). Concentrations are consistently higher in the Pacific than in the Atlantic. This cold nutrient-rich water can be artificially upwelled by pumping the water through a vertical pipe and then distributing it to the plants on the surface by a network of horizontal pipes.

The complexity of the distribution system will depend on the capacity and number of upwelling pumps and will ultimately determine the size of the farm unit. For instance, a few high capacity upwelling pumps would require an extensive distribution system, whereas many low capacity pumps would require a less extensive distribution system. Because the surface horizontal pipes obstruct movement of seafaring vessels, including harvesting ships, the size of the farm unit will be limited by configuration of the distribution system and interlocking pumps. The distribution pipes must be close enough together to fertilize all the plants, taking into account horizontal and vertical water movement, yet far enough apart to allow the movement of harvesting ships. The problem of ship movement is reduced somewhat if the horizontal pipes are placed deep enough to avoid obstruction. Vertical pipes radiating from the horizontal ones would then be required for distributing the nutrient-rich water. Nevertheless, these vertical pipes must occur frequently enough to provide nutrients to all the plants.

The pumps may be powered by conventional fuels or, providing environmental forces are sufficiently abundant, by hydrodynamic or wind energy,



Depth (m)	NO_3-N µg-atm/L VI	Gulf	Atlantic	Pacific
0	0.08	2.4	0.10	2.5
100	1.5	2	5	5
200	3	7	9.5	9.5
300	8	13	16	18
400	14	19	20	24.5
500	20	25.5	23	29.5
600	23	31.5	26	32
700	22	36.5	29	33
800	20	37	30	34
900	18.5	36	29.5	35
1000	16.5	35	29	35.5

Figure 3.9

Vertical Distribution of Nitrates in the Virgin Islands Basin (69), the Gulf of Mexico (70), and Tropical and Subtropical Regions of the Atlantic and Pacific Oceans (71).

or possibly even by solar or thermal energy. The upwelling system must have the capacity to pump up large quantities of water to satisfy the needs of the plants and to compensate for head loss in the distribution system. The amount of water needed by the plant depends on the nutrient content of the water being upwelled and that of the surface waters, the length of time nutrients are retained near plant surfaces and the efficiency of nutrient uptake by the plant. Because of the temperature differential, water retention time may be a key factor affecting the design of the upwelling system. Cold water will sink quickly when it comes in contact with warm surface waters, thus limiting the time available for nutrient uptake by the plants. Unless the temperature differential is lowered, an increase in the quantity of cold upwelled water would have to compensate for nutrients sinking too quickly to be utilized by the plants. If small diameter pipes are used in the upwelling and distribution systems, frictional forces will warm the upwelled water significantly and if the distribution system is extensive, prolonged contact between the narrow pipe and the warmer surface waters will reduce the temperature differential. The structural integrity and cost of such piping must be taken into account, however. A trade-off exists between pumping large quantities of water through large pipes and pumping smaller quantities of water through smaller diameter pipes. Ultimately, the decision will be based on economic and energy costs of the system.

Another potential nitrogen source, denoted by "recycle" in Figures 3.1 and 3.2, is the sludge from the digestion process. Anaerobic digestion of biomass slurry results in the release of methane and carbon dioxide, leaving a residual slurry (Figure 3.10). This sludge contains approximately 40% of the nutrient value of the original biomass. If the sludge can be pretreated to convert the nitrogen into a form utilizable by the plants, then the recycling of this sludge may contribute significantly to the fertilization of the farm, and at the same time relieve the problem of waste disposal from the processing plant. If the processing plant is not at the farm site, the sludge may be transported from the processing plant to the farm by the same vessels carrying plant biomass to the processing plant. At the farm site,

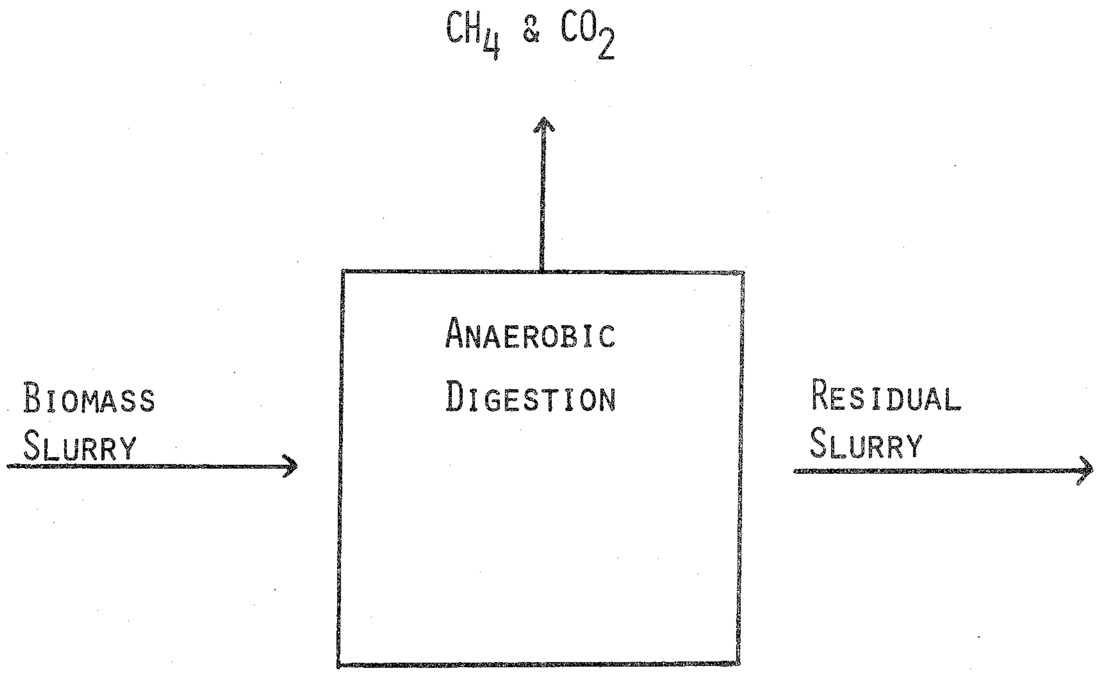


Figure 3.10

Diagram representing anaerobic digestion input and output.

Table 3.4

COMMERCIALLY AVAILABLE NITROGEN SOURCES
Prepared Media
Domestic Sewage
Animal Manure
Potato Processing Wastes
Meat Processing Wastes
Reduction Plant Wastes
Petroleum Refinery Wastes

the sludge would be distributed to the plants by the harvesting vessels. Although the use of recycled sludge is attractive, it must be kept in mind that the sludge not only contains high concentrations of nutrients, but also high concentrations of other substances readily absorbed by the plants - including heavy metals and other toxicants polluting the water. Before these substances are released into the environment, their effects on the metabolism of plants and animals must be considered.

A number of potential commercially available nitrogen sources, all of which are in limited supply, might be used to satisfy a portion of the nutrient requirements in mass cultivation (Table 3.4). Although precisely defined man-made media may be prepared to provide the exact nutrients and micronutrients required by plants, this fertilizer is not considered practical or necessary for mass cultivation. A more practical approach is to dispose of organic waste products on the farm, once they have been pretreated and devoid of toxic materials.

After nitrogen, from any of these sources, has been converted into a form utilizable by seaweeds, nutrient absorption takes place directly through plant surfaces. For example, the majority of plant surface area occurs in the top 1 m of the Macrocystis bed canopy, so most nutrients are taken up there. Nutrients will continue to be taken up by the lower portion of the plant, however, as the nutrients descend in the water column to as much as 30 m deep.

3.2.2 Cultivation of Floating Marine Macroalgae

Floating macroalgae, such as Sargassum (Figure 3.11) which do not require attachment to a substrate and are held on the water surface by means of air bladders or pneumatocysts, may be cultivated in the open ocean (Figure 3.12) and in coastal waters (Figure 3.13) in systems similar to those described for attached plants with modifications on the support element, containment and harvesting. Since the life cycle of these floating plants does

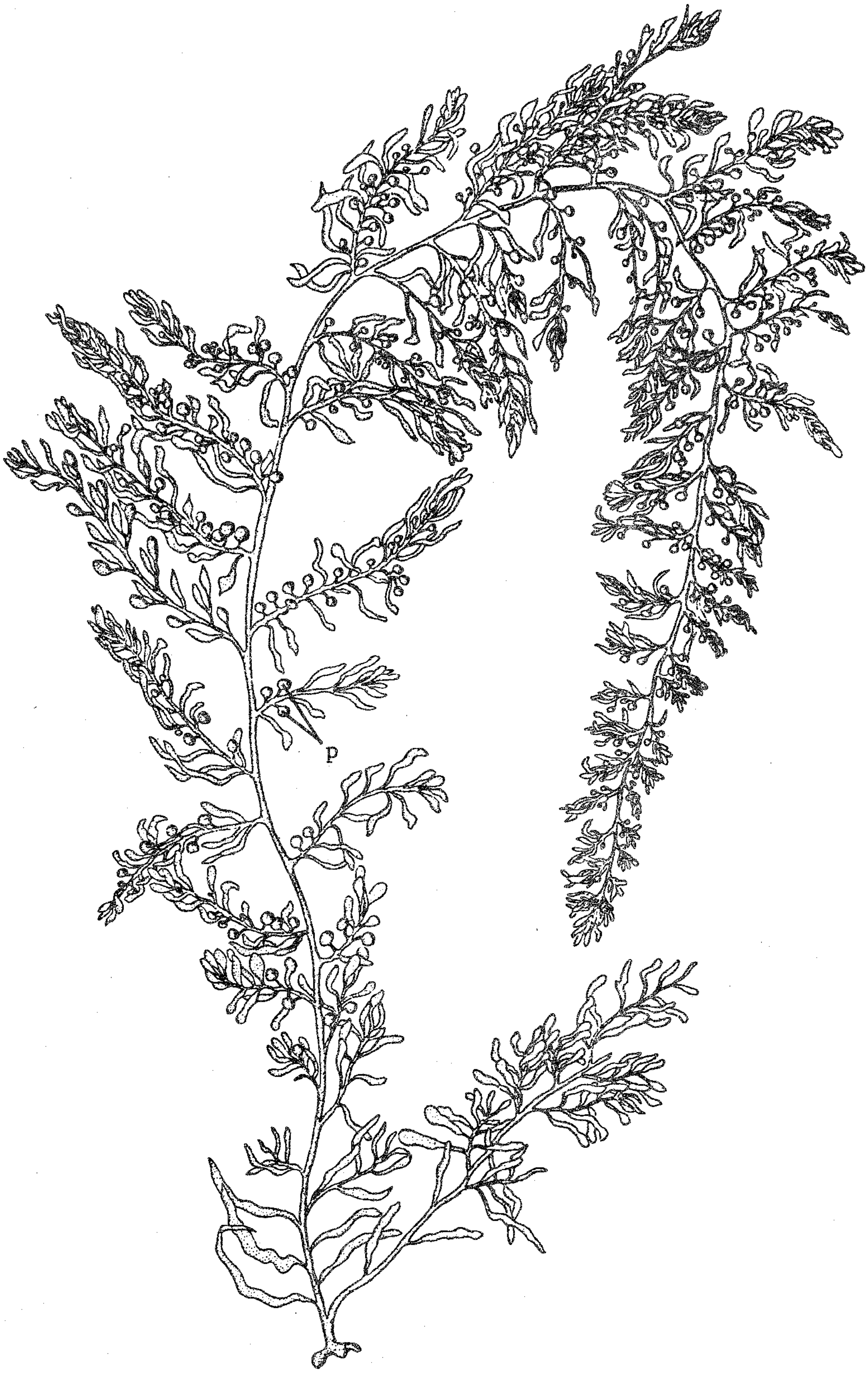


Figure 3.11

Sargassum muticum x 1.9 (72)

p, air-filled pneumatocysts buoy plant to the surface

Figure 3.12

OPEN OCEAN SYSTEM

CULTIVATION OF MARINE MACROALGAE FLOATING ON SURFACE

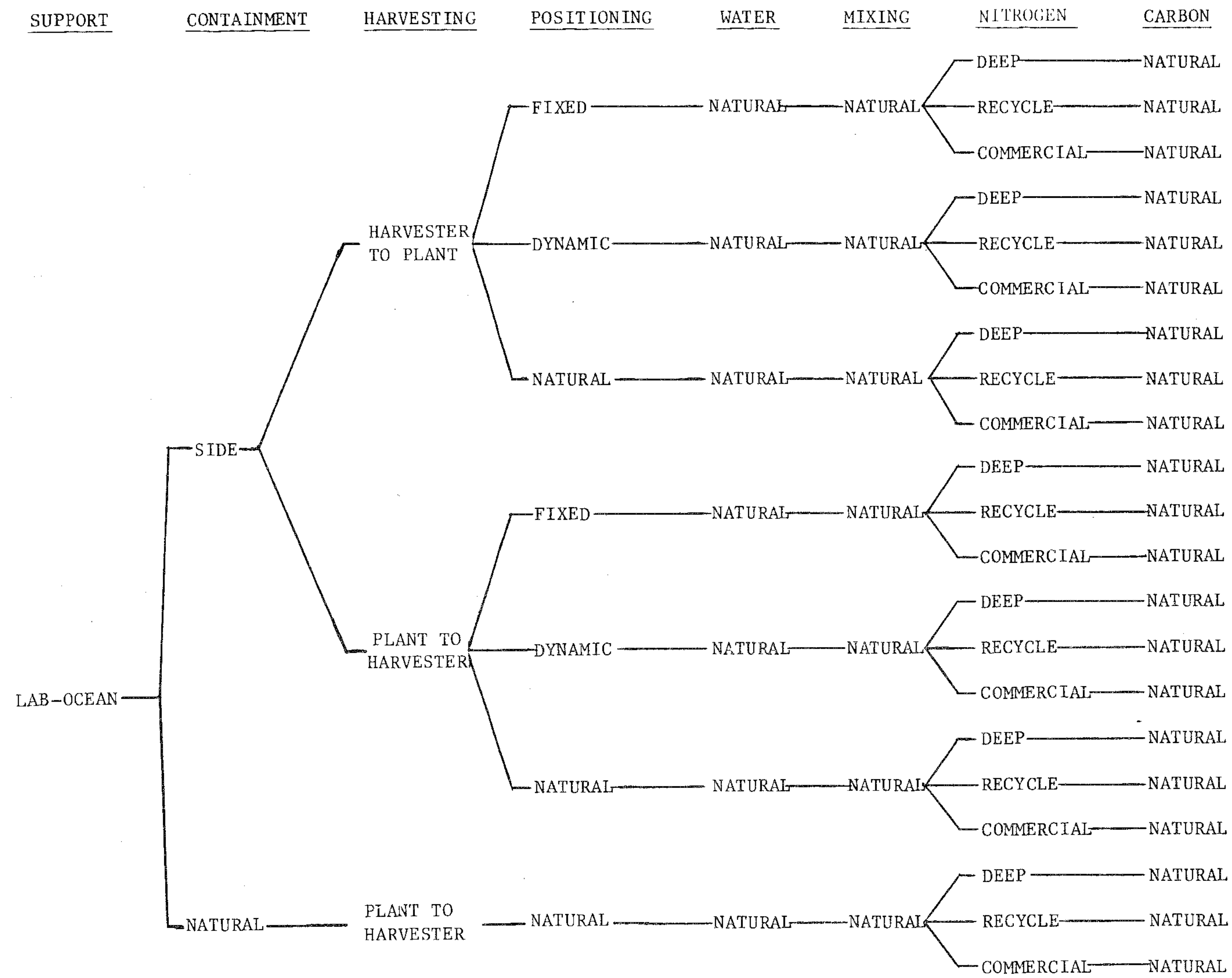
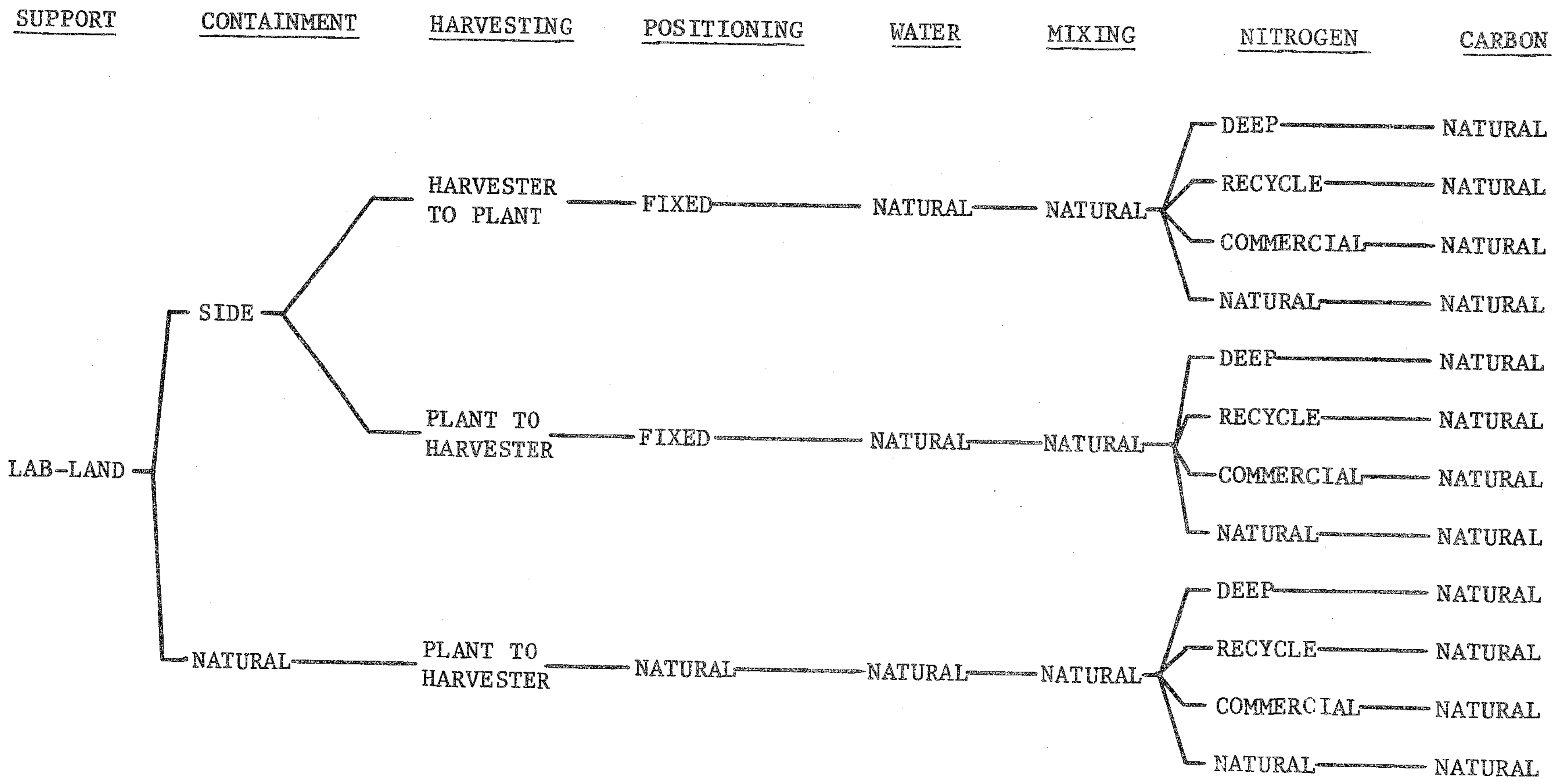


Figure 3.13

COASTAL SYSTEM

CULTIVATION OF MARINE MACROALGAE FLOATING ON SURFACE



not involve attachment of a sexual reproductive stage, extensive laboratory facilities are not needed to stock the farm. These seaweeds would be introduced to the farm by simply breaking the seaweed into pieces and allowing them to spread over the water's surface by vegetative growth. Nutrient requirements for the growth of floating plants are similar to those of the attached plants (see Section 3.2.1). Since floating plants only occur within the top .5 m of the water column, retention time of nutrients in that area is critical. Therefore, selection of nitrogen source and development of a fertilization method must take into account the sinking rate of the nutrients.

The perimeter of the farm would be fenced in to contain floating plants. The fence would be supported by fixed structures in relatively shallow waters (Figure 3.14) or by tethered buoys in deeper waters (Figure 3.15). Since floating plants drift with surface waters, they may also be contained "naturally" within a well-defined circulating current system. Lack of control of such a system would, however, present extensive problems with monitoring and maintaining crop density, fertilization, harvesting and legal matters.

Entire floating plants may be easily harvested without entanglement in a substrate, leaving a portion of the standing crop to replenish the culture. The unharvested portion is not lost from the system as in the case of the lower portion of the cut stipe of _Macrocystis_. Loss of the floating plant biomass is limited to normal mortality. As indicated in Figure 3.12 and 3.13, there are two options for harvesting floating plants: 1) the harvester moves to the plants (see Section 3.2.1), or 2) the plants drift with water movement to the harvester. The latter option is illustrated in Figure 3.16. Energy generated by surface currents moves the floating plants into one area where they are concentrated and then picked up by the harvester. This option is highly dependent on weather conditions.

3.2.3 Cultivation of Suspended Marine Macroalgae

Marine macroalgae grown in suspended culture include a wide variety of seaweeds such as _Gracilaria_, _Chondrus_ and _Eucheuma_ which in the natural

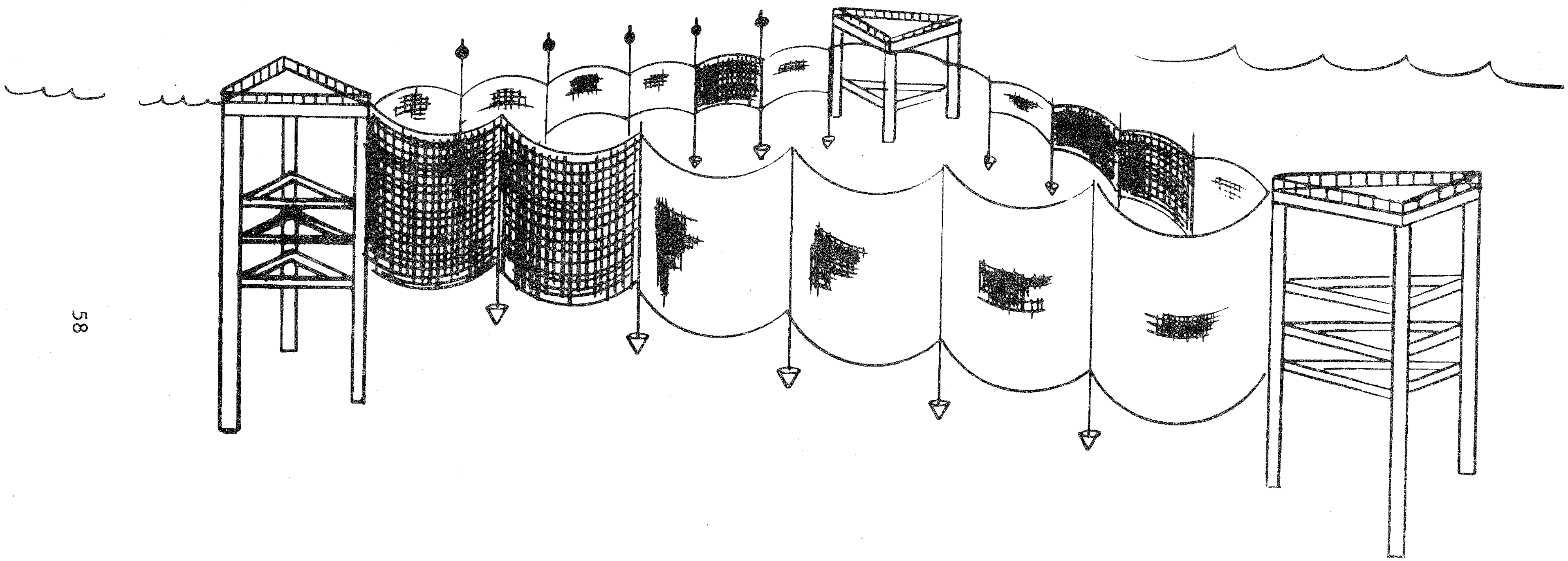


Figure 3.14

Diagrammatic representation of fixed structures supporting a fence.

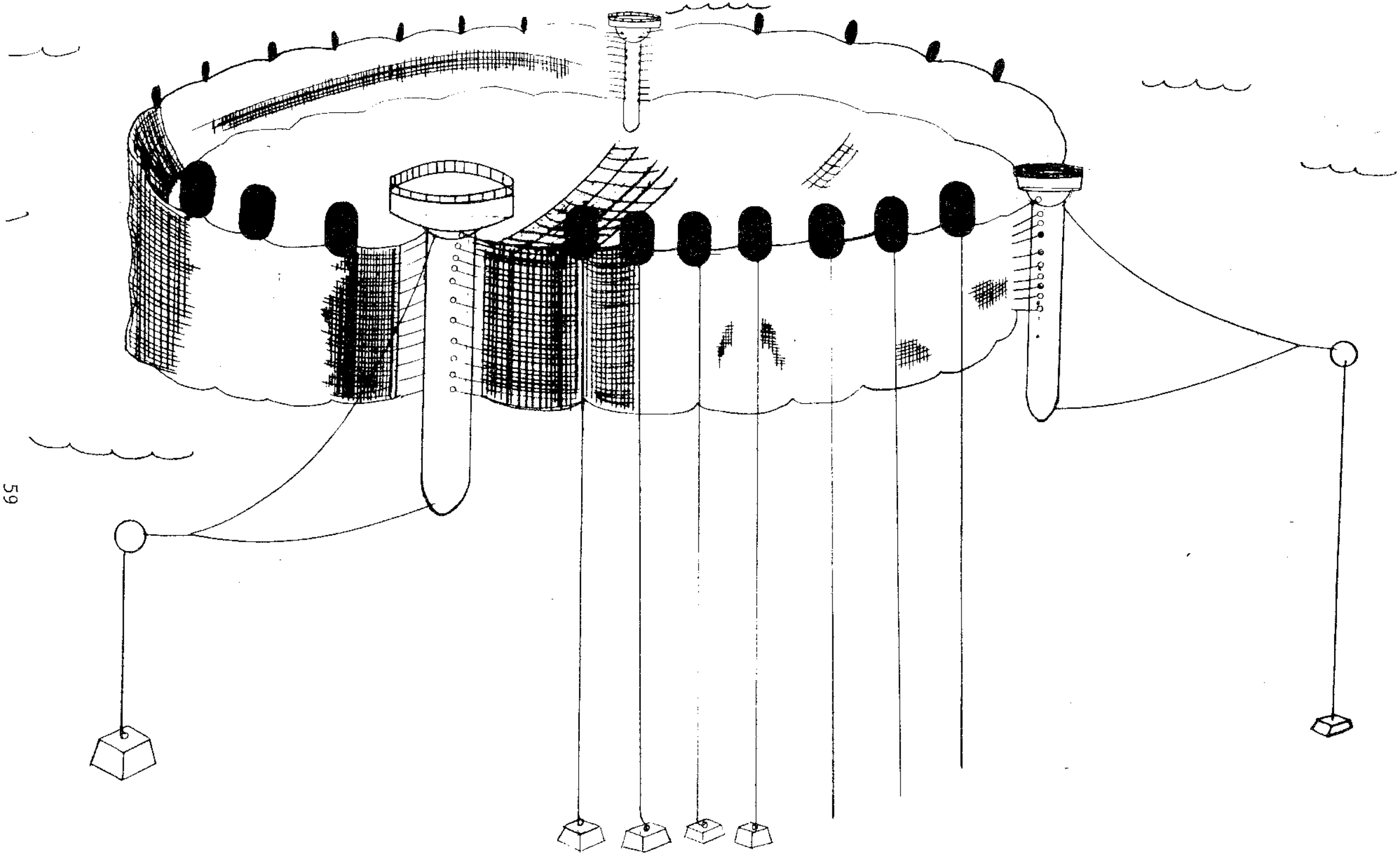


Figure 3.15

Diagrammatic representation of a tethered system for containing plants with a fence. Spar buoys and smaller buoys hold the net on the surface and anchors keep the system in tension.

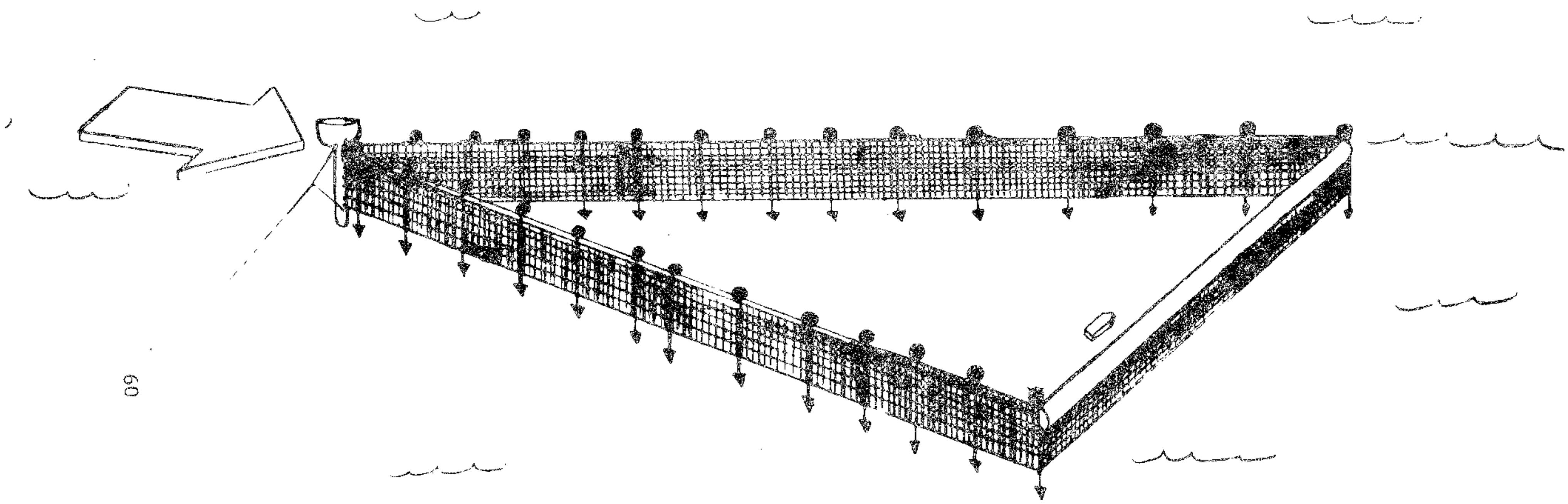


Figure 3.16

Diagrammatic representation of system for harvesting plants moving to the harvester in the open ocean. The current direction, represented by an arrow, is moving from left to front right. The fence is held open by buoys and weights, and the whole system is anchored at a spar buoy. As floating plants drift with the current, they concentrate in one area to be harvested.

environment are unattached or have both attached and unattached stages. Unless these seaweeds are artificially buoyed up, they sink to the bottom. They therefore must be contained in a specified area not only on the sides, but also from below. Although they may be cultivated in coastal waters in a system similar to that shown in Figure 3.2 for attached plants, problems with containment, mechanical harvesting and providing adequate mixing within the containers, suggest that the system is best controlled on the shoreline.

Attached, floating and suspended marine macroalgae may be cultivated in a shoreline system like that outlined in Figure 3.17. The farm is stocked initially from a land-based support facility either allowing spores of attached plants to settle on nets in the enclosure or by innoculating the culture with pieces of floating or suspended seaweeds. As indicated under "containment", the enclosures in the form of ponds or raceways, may be lined or unlined, depending on the sediment composition. Enclosures constructed from sandy soils, with a clay content of 25% to 75% usually do not need to be lined if spaces between sand particles are filled with silt or organic debris. When lining is necessary however, a sealant like bentonite clay, salts such as sodium chloride or polyphosphate, or materials such as plastic or rubber may be used.

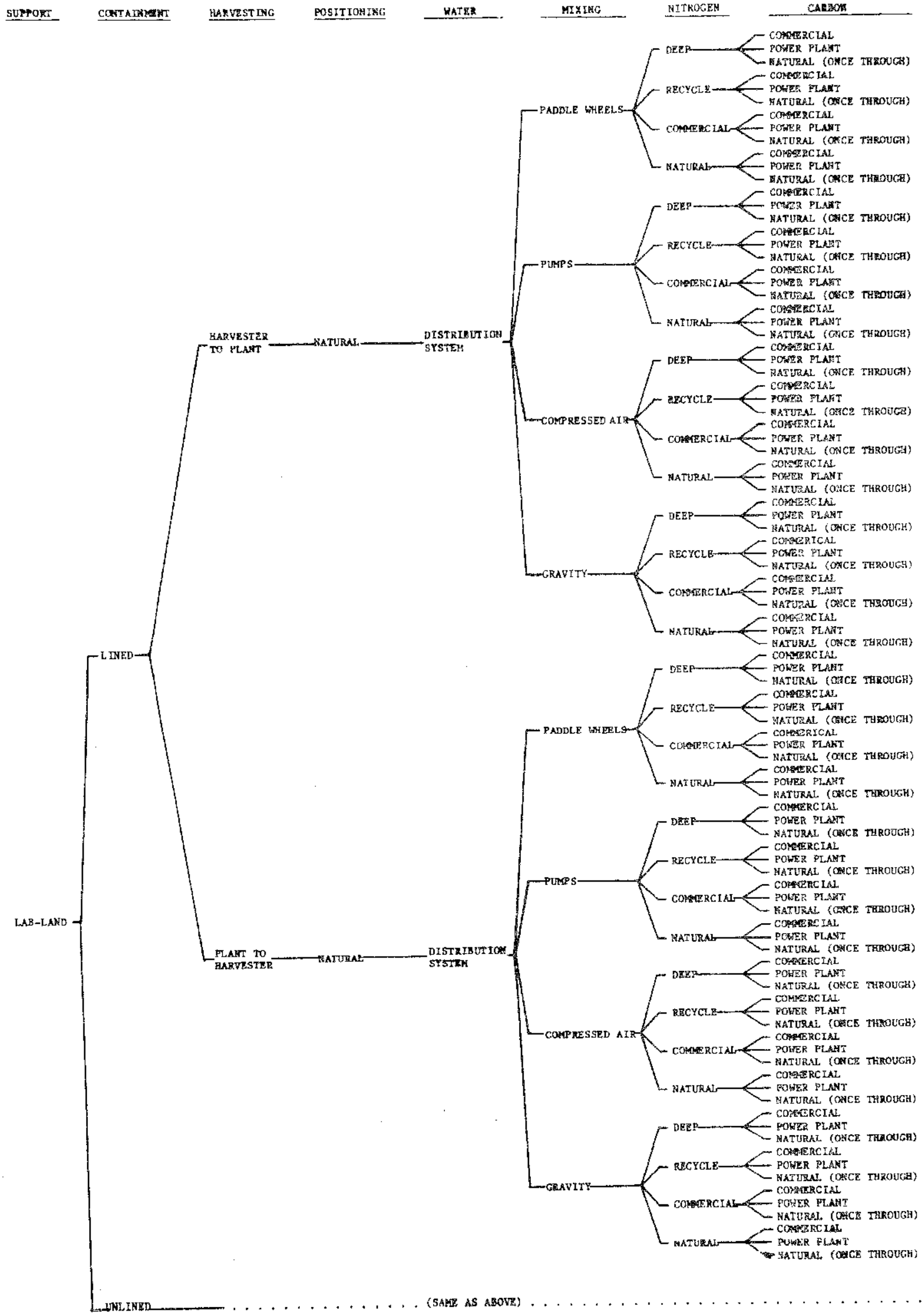
Harvesting marine macroalgae can be easily performed in a shoreline system. As floating or suspended seaweeds drift with water movement past a particular point, a portion of the standing crop may be simply separated and removed. Attached plants may be harvested by pulling them from their net substrates.

Although an unlimited supply of marine water is available to the shoreline system, it must be piped to the farm, distributed throughout and mixed to provide adequate transport of nutrients. There are four alternative methods to move water over the 100 square mile area: paddlewheels, pumps, compressed air and gravity. If adequate mixing is provided, nitrogen from sources described previously (see Section 3.2.1) may be utilized with a maximum efficiency

Figure 3.17

SHORELINE SYSTEM

CULTIVATION OF MARINE MACROALGAE



since the retention time is controllable. Unlike systems in coastal areas and the open ocean, there is no problem with loss of nutrients from the system. High rates of mixing and a rapid water exchange are particularly important in a shoreline system since transport of carbon dioxide from the atmosphere can not keep pace with algal assimilation during intense plant growth, and a resulting rise in pH may be detrimental to the crop. Careful control of pH would be maintained by the addition of carbon or by quickly moving seawater through the system before the carbon naturally occurring in the water is totally depleted. Although the supply is limited, carbon is commercially available or it may be obtained as a by-product of the digestion process from the power plant. Whatever the source, adding carbon to the system also means adding a network of pipes to distribute the carbon.

3.3 Cultivation of Marine Angiosperms

Seagrasses (Figure 3.18), the only true rooted marine angiosperms, naturally occur at depths ranging from 1 to 20 m depending on the clarity of the water and the incident solar radiation reaching plant blades. The plant consists of long flat slender blades which produce carbon by photosynthesis and are held to the substrate by a root system. Unlike marine algae these plants absorb nutrients from the sediment by their roots, not directly through all plant surfaces. Because of their dependence on nutrients from the sediments, seagrasses must be cultivated on a natural substrate, usually a mud and sand mixture.

As shown in Figure 3.19, a cultivation system for seagrasses is relatively uncomplicated involving few options. Containment and positioning requirements are satisfied by natural attachment to the substrate. Initial stocking of a seagrass farm may be achieved by transplanting small clumps of plants along with their original substrate from existing seagrass beds. Runners extending horizontally in all directions from the clumps will spread to form a mat which appears much like a terrestrial lawn. Similarly seagrasses may be harvested by a "lawn mower" harvester which cuts the blades, leaving the root system behind to regenerate new blades.

a) b)

Figure 3.18

The Marine Seagrasses (73)

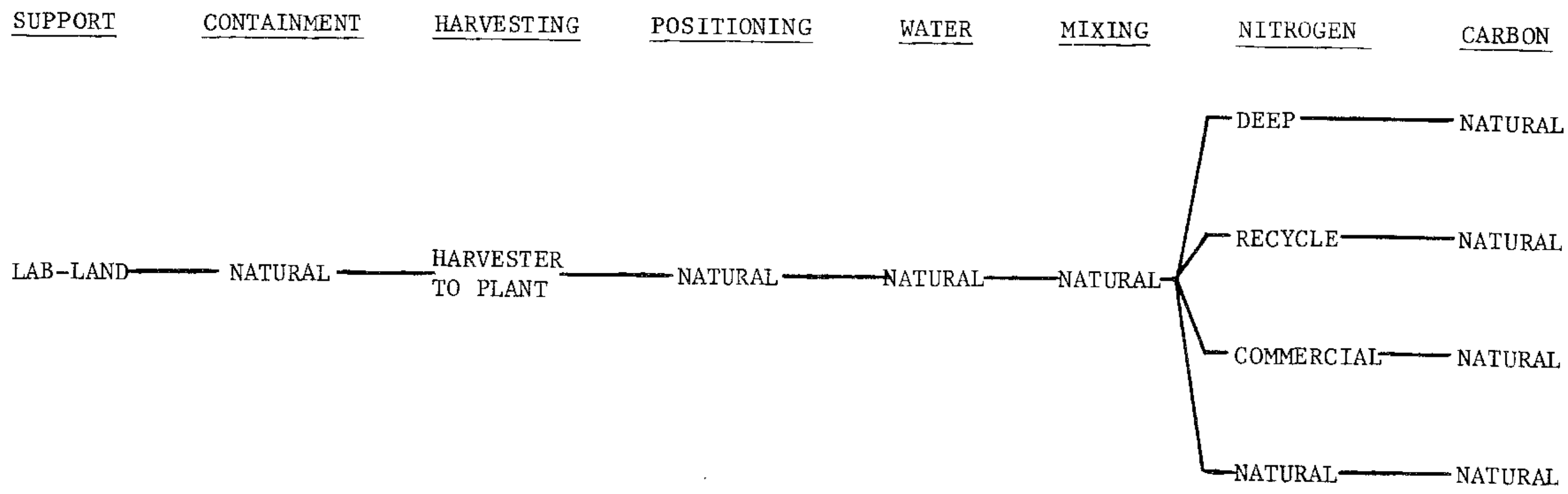
a) Zostera marina x 0.3 showing knobby rhizone, adventitious roots, and linear leaves

b) Thalassia testudinum x 0.3 with staminate flower

Figure 3.19

COASTAL SYSTEM

CULTIVATION OF MARINE MACROPHYTES ATTACHED TO A NATURAL SUBSTRATE



Seagrasses do not require rapid mixing of water like most aquatic plants. In fact, their blades act as baffles to calm water movement, so that detrital material accumulates to form a thick nutrient-laden sediment. Nitrogen sources described previously (see Section 3.2.1) - deep water, recycled sludge from the digestion process, and commercial sources - may be added to the natural seawater to enhance growth. However, due to the accumulation of detrital material from the vast assemblage of organisms in seagrass beds and of organic material descending from the land into coastal waters, the naturally available nutrient content of the water and sediment is usually high. The major advantage that marine seagrasses have over other aquatic plants grown in the natural environment is their ability to absorb nutrients from the sediments, since nutrients are retained there indefinitely until they are needed by the plants. The seagrasses then serve as "nutrient pumps" recycling nitrogen and other necessary elements.

3.4 Cultivation of Freshwater Angiosperms

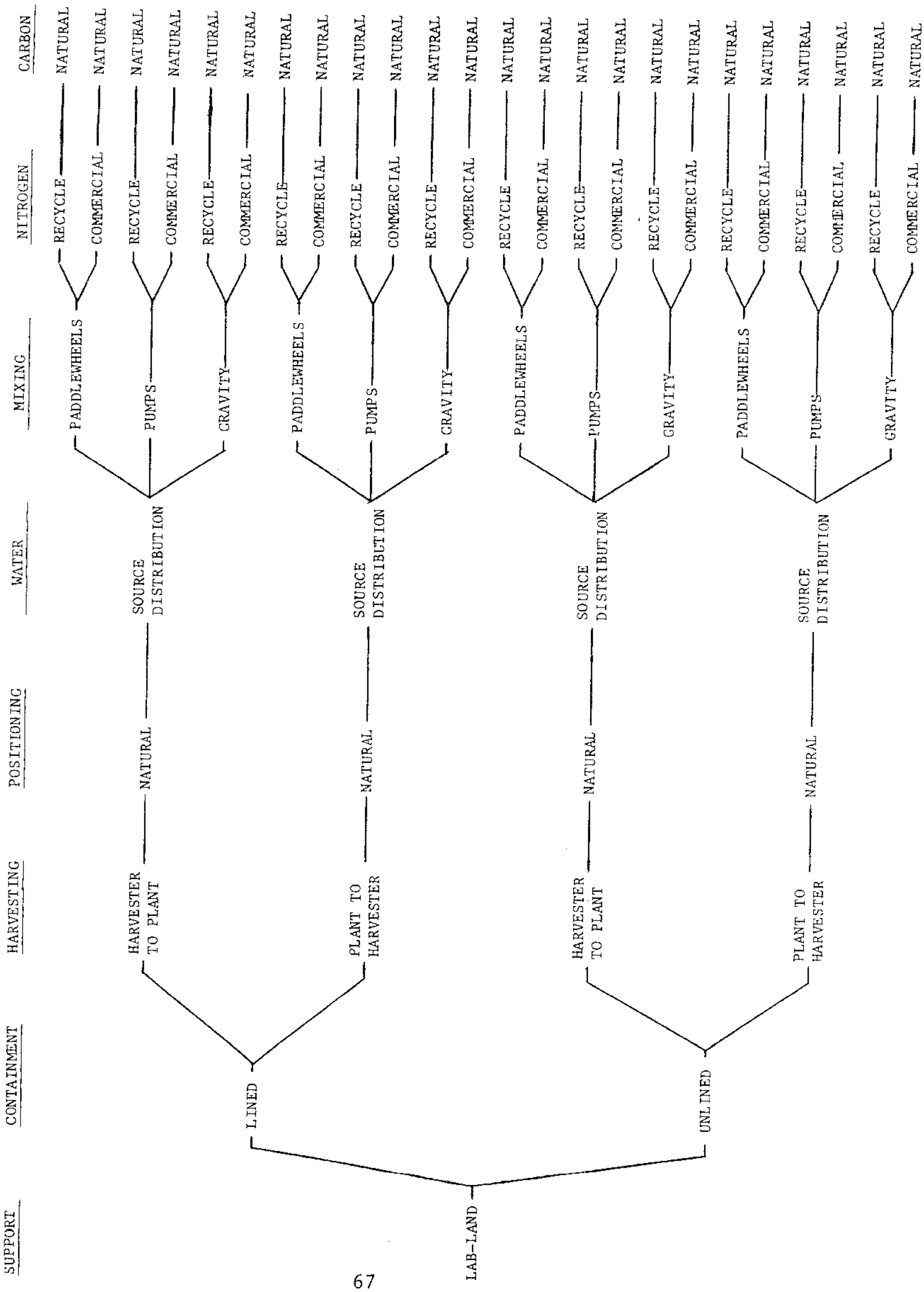
A cultivation system for freshwater angiosperms is shown in Figure 3.20. The freshwater angiosperms occur naturally in lakes, ponds, rivers and canals in tropical and subtropical regions. Since several species are particularly notorious for their abundance and rapid growth rates, they are commonly called "freshwater weeds". These include emergent species such as the water hyacinth *Eichhornia crassipes* (Figure 3.21) and the duckweeds *Lemna* (Figure 3.22a) and *Wolffia* (Figure 3.22b) of which only the roots are in the water, and the completely submerged species such as *Hydrilla* (Figure 3.22c).

Although they produce true flowers and seeds, they also propagate vegetatively and it is by this means that their most efficient, sustained organic productivity is achieved. The farm may be easily stocked by adult plants which will quickly regenerate and spread over the water's surface. As in a shoreline system, the plants may be held in a lined or unlined container (see Section 3.2.3). Since these plants usually float at or near the surface, an increase in suspended material in an unlined container will not decrease the amount of solar radiation reaching the plants and therefore will not affect the photosynthetic rate.

Figure 3.20

INLAND SYSTEM

CULTIVATION OF FRESHWATER MACROPHYTES



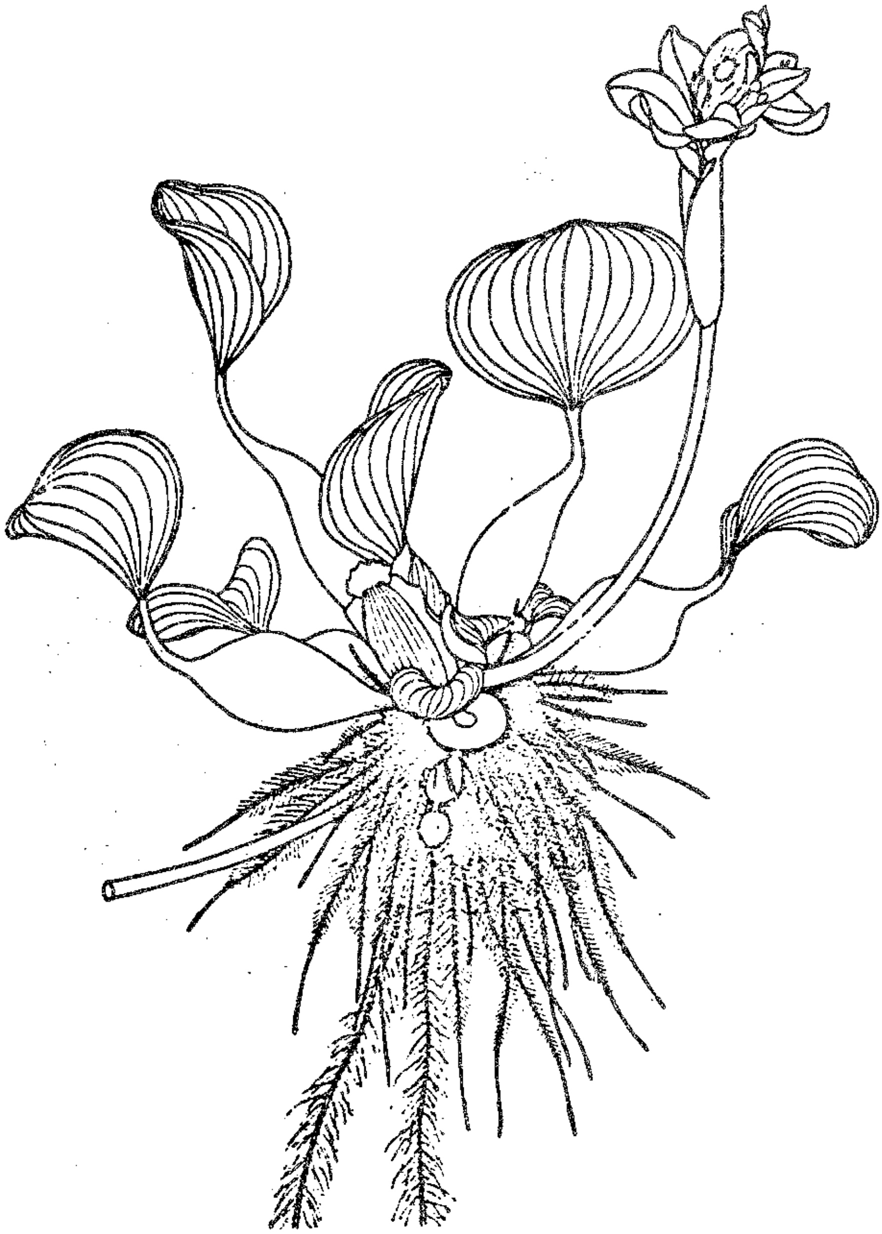


Figure 3.21

The Freshwater Angiosperm (75)

Eichhornia crassipes x 2.8

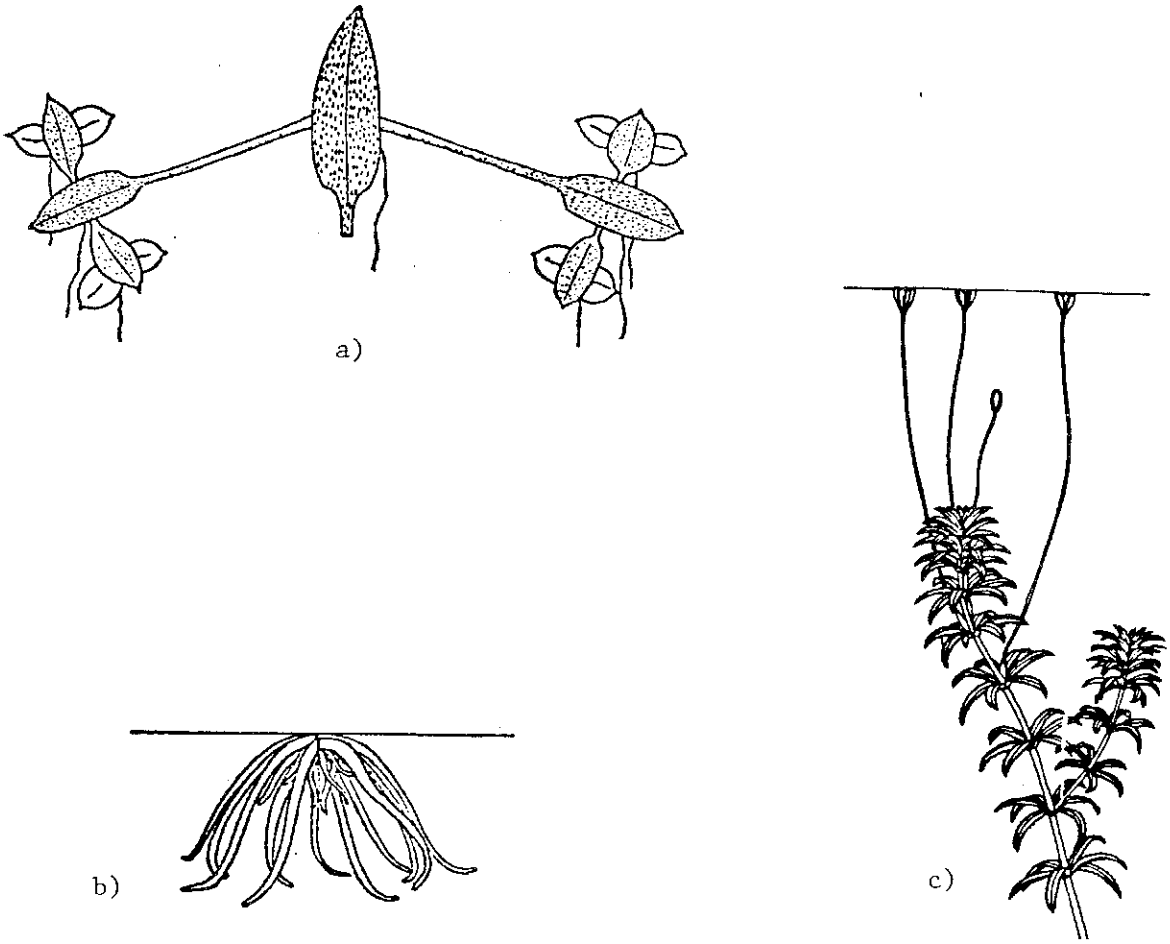


Figure 3.22

The Freshwater Angiosperms

a) Lemna trisulca x 4 (74)

b) Wolffia floridana x 4 side view showing water line (74)

c) Hydrilla verticillata x 1.7 (75)

Most freshwater angiosperms do not require a rapid water exchange, but grow well as long as they are kept moist. Increasing water movement does increase growth rate, however, so mixing by paddlewheels, pumps, or gravity is desirable. Flowing water can also provide energy for harvesting. While drifting with the water movement, these floating plants would be diverted to the shore by a boom across the water and harvested by a conveyor belt. Such a mechanical harvester has been used successfully in Florida.

Freshwater plants incorporate nitrogen into new cell biomass by an absorption process, the efficiency of which is maximized under anaerobic conditions. Therefore, they grow well when tightly packed so that anaerobic conditions exist below the plants. They may be fertilized by recycled sludge from the digestion process or by commercial sources to satisfy nitrogen requirements (see Section 3.2.1). These plants are particularly well known for taking up and storing large quantities of nitrates and phosphates, as well as industrial pollutants, heavy metals, pesticides and herbicides from polluted waters. Unlike all the other aquatic plants, freshwater angiosperms do not obtain carbon from the water, but rather directly from the atmosphere. Therefore, it is not necessary to provide additional carbon dioxide from artificial sources.

3.5 Marine, Brackish and Freshwater Microalgae

Microalgae are quantitatively the dominant plant form in freshwater and in the open ocean. Morphologically they are single cell plants growing as individual cells or aggregations of cells in the form of chains or filaments (Figure 3.23), which range from two micrometers to as much as a millimeter in diameter. Those species which are weakly motile or buoyant, float on the surface or are suspended in the water often as part of the plankton. Other forms sink and form matts of slime layers on the bottom. When light, temperature, nutrients and other environmental parameters are favorable, colonies of microalgae reproduce to dense concentrations or "blooms" which may be aesthetically displeasing and ecologically damaging.

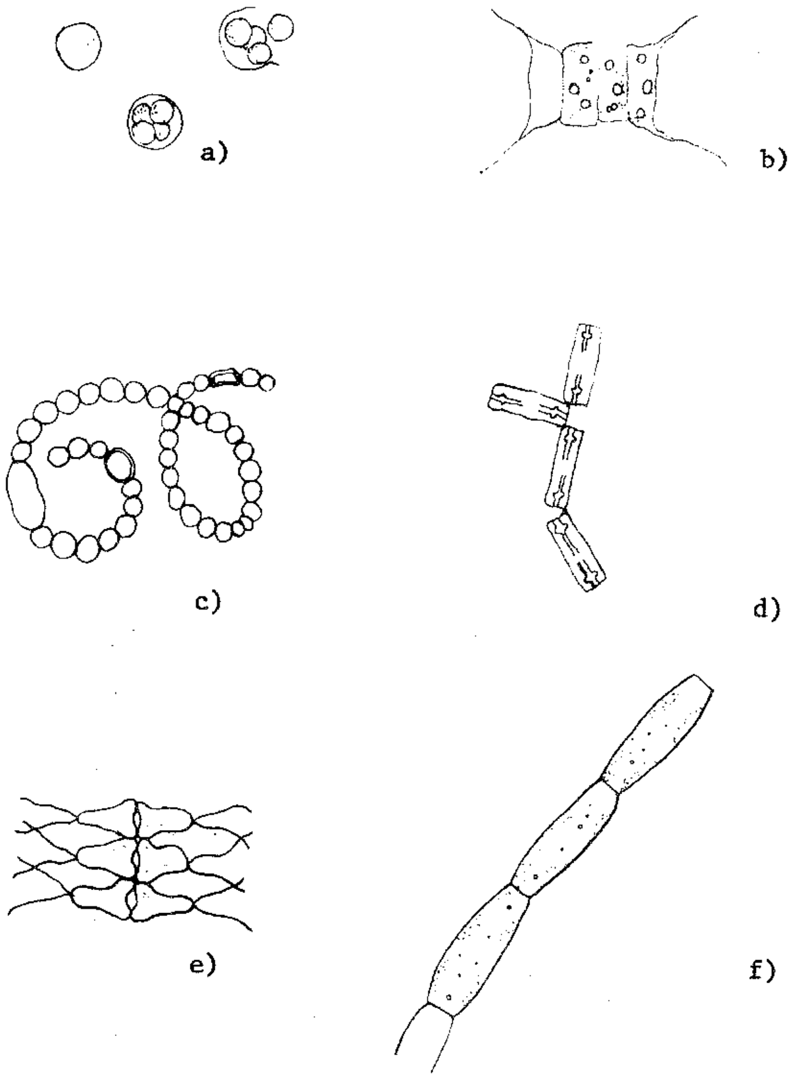


Figure 3.23

Microalgae

a) Chorella single cell and formation of autospores
b) coenobial type Scenedesmus
c) filamentous type Anabaena
d) colony of Grammatophora
e) flagellate colony of Chlorodesmus
f) filamentous type Tribonema

Due to their small size and hence, difficulty in containment, the cultivation of microalgae is limited to a land-based freshwater or marine system. In many respects, a cultivation system for microalgae (Figure 3.24) is similar to the shoreline system for macroalgae (see Section 3.2.3) except for a few fundamental differences, because of their small size.

The microalgal farm may be stocked by innoculating the culture with the desired species and providing optimal conditions for growth of that species. Even under optimal conditions, however, species control is difficult because of natural fluctuations in microalgal populations. If no particular species is required, microalgae naturally occurring in the culture media will bloom without innoculation if nutrients are added.

As discussed previously for the macroalgal shoreline system (see Section 3.2.3), the container for microalgae may be lined or unlined. However, if unlined, it is particularly important that the sediment remain out of suspension so that silt does not decrease light penetration and is not harvested with the plants.

Harvesting is often considered the single most difficult problem of mass cultivation of microalgae. As indicated in Figure 3.24, three harvesting techniques were considered for analysis: centrifuging, microstraining, and decanting.

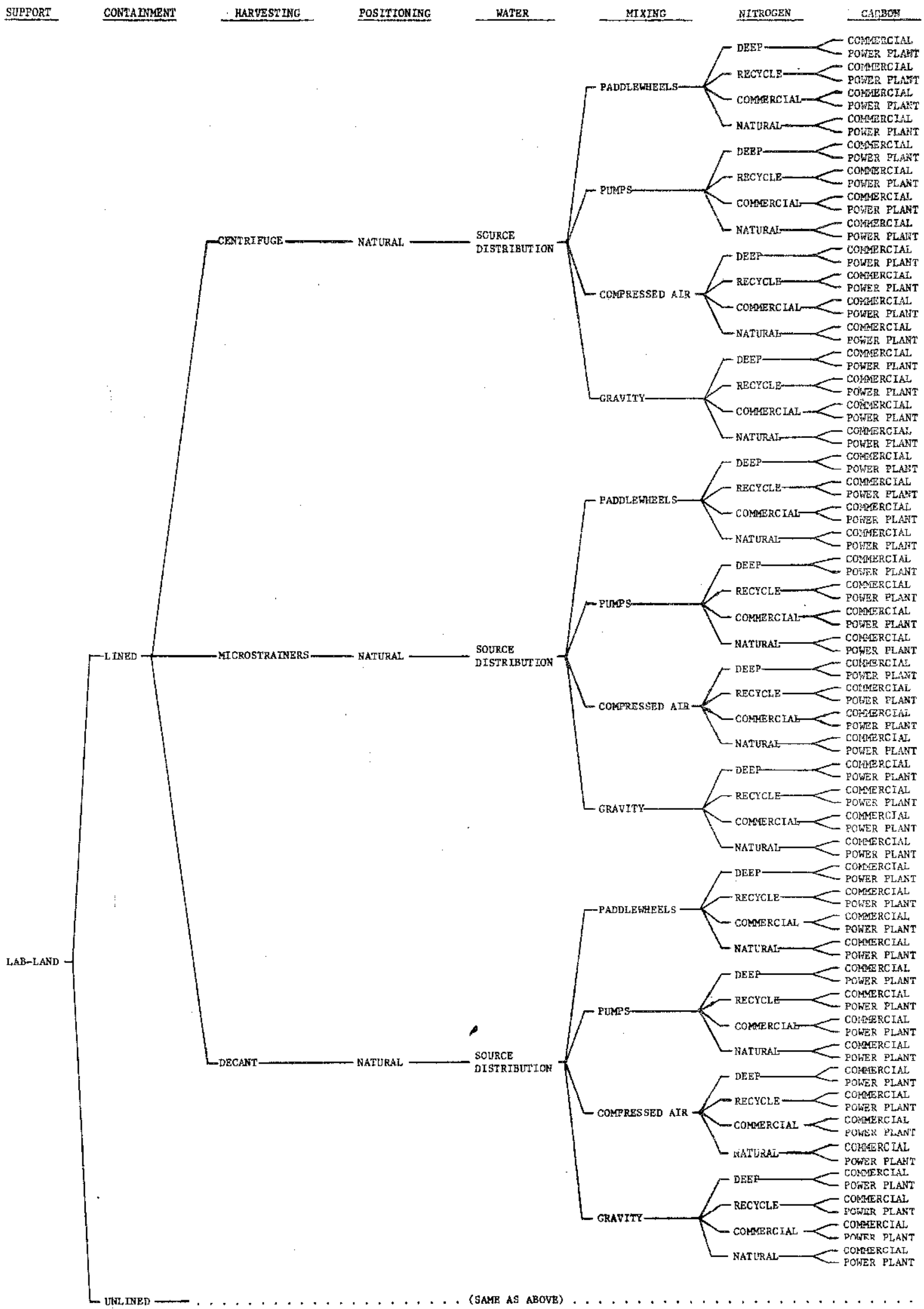
Centrifugation is a relatively simple process and is equally successful with all microalgal species. However, in mass cultivation this process requires a great deal of equipment and energy.

Some filamentous or colonial microalgae can be harvested by straining through very small-mesh screens, but the screens tend to clog so that water will not pass through. Frequent backwashing is needed and because so much backwash water is required, the efficiency of the process is low. A modified paper machine, which overcomes this problem somewhat, collects the microalgae on a continuously moving cellulose filter. The feasibility of using such a device is dependent on cost and on the digestibility of the filter and attached microalgae to produce methane.

Figure 3.24

SHORELINE AND INLAND SYSTEMS

CULTIVATION OF MICROALGAE



Decanting concentrations of microalgae floating on the surface or settling to the botton is another effective method to harvest microalgae. Although many species of microalgae naturally float and settle periodically, control of this process to date has been successful only by the addition of chemicals to promote coagulation and subsequent flotation or sedimentation. This is potentially the most economical and effective process available, if control of a particular species can be achieved and if the proper conditions required for the concentration of that species can be defined.

Section 4

ENGINEERING DESIGN CONSIDERATIONS

4.1 Introduction

An aquatic biomass growth system is defined here as any system in which aquatic or marine biomass (excluding soil-rooted plants) is grown in a body of water. This system definition includes an enormous number of possible combinations of biomass species, flow regimes, and other parameters which can vary. The following analysis will not attempt to be comprehensive; rather, the purpose is to present representaitve calculations to point out what can or must be done (from an engineering standpoint) to meet system needs for some combinations. These needs can be defined, for example, in terms of carbon dioxide provision, nutrient provision, and the necessity for adequate mass transfer of these components to the biomass.

Reference is made to discussions of some aspects of aquatic biomass growth systems which have been presented by Goldman (76), Oswald and Benemann (77), and Wilcox et al (78). The purpose here is to provide some additional quantification, particularly in areas where questions were raised in those references. An over-all objective is to further evaluate prospects for technical and economic feasibility of these systems. The scope of this analysis will be restricted to the growth process only, that is, harvesting and conversion to energy are not considered. These will need to be the subject of separate studies.

Although the following analysis is not exhaustive, it is worth noting that prospects seem encouraging for technical feasibility for some of the possible biomass growth systems. However, there are also a number of approaches which do not appear to be practical, and computations concerning these approaches are included for reference.

Conditions chosen for this evaluation are shown in Table 4.1. This choice of composition and yield range established nutrient and carbon dioxide requirements for purposes of computation. For some calculations, a specific value, rather than a range, will be assumed for example purposes and order of magnitude determinations. It will be demonstrated later that a change in these assumptions will not affect most conclusions. One change in these conditions was made when considering open-ocean giant kelp farms, namely, a plant nitrogen content of 1.6% on a daf basis.

4.2 Nutrient Utilization for the Open-Ocean System

Nutrient utilization efficiency is defined as that percentage of upwelled nutrient absorbed by the plant. Estimates of this efficiency have been made (79), but no definitive analysis of the parameters governing utilization efficiency has been produced. A range of nutrient utilization efficiencies are presented to demonstrate the effect of this parameter on other farm design parameters.

Nutrient utilization parameters fall under two major headings: flow patterns of nutrient-rich water from distribution pipes through the farm and mass transfer of nutrient from ocean to plant tissue. Considerations which must be determined in order to predict farm performance under the flow pattern heading include sinking rate and effect of current and wave motion.

4.2.1 Sinking Rate

An experimental study conducted by P.F. Seligman (80) for the Naval Undersea Center in San Diego, California, reported that the vertical sinking rate of water pumped from a depth of 1,000 feet through a 10-inch diameter pipe, outlet at 10 feet below the surface of the water with an upward velocity of approximately 22 cm/sec and at a rate of 180 gal/min, was 0.2 cm/sec and 0.064 cm/sec in two runs. Upwelled water was determined

Table 4.1

ASSUMPTIONS FOR
AQUATIC BIOMASS GROWTH SYSTEM

Algal Composition (DAF)[1]

C = 45%

N ≈ 3% (P = 0.1 N = 0.3%)[2]

Higher heating value (DAF) = 8,000 BTU/lb.

Yield = 1 - 50 Tns/Acre/Year

Area = 100 sq. mi. = 64,000 Acres

Total Gross Energy Output (G.E.O.) =

1.0×10^{13} BTU/Yr. = 0.01 Quad.

Total Product Fuel Yield = 5×10^{12} BTU/Yr. = 0.005 Quad.

1. Dry, Ash Free
2. For Kelp, N = 1.6%

to remain in the top 10 feet for thirty minutes and the top 6 feet for forty minutes in the two runs. Because of vertically upward flow from a 10 foot depth to the surface, considerable mixing of upwelled water with warmer surface water was expected to occur. Water released at the surface with no initial vertical velocity and no mixing may tend to sink faster than the mixed water of the Seligman experiment, which had a vertically upward velocity.

An analysis utilizing a digital computer based on a method derived to determine Ocean Thermal Energy Conversion (OTEC) cold water plume dynamics for a large volumetric flow rate point source performed at the Hawaii Laboratory of the Naval Undersea Center (81) reported sinking rates of between 7.6 feet/min and 10 feet/min (3.2 to 4.2 cm/sec). Buoyancy considerations dictate that colder, more dense upwelled water will sink in the presence of surface water. Appendix D details this method of water sinking rate calculation, and states that for a density difference of approximately 0.4%, the sinking rate varied from 1.8 to 130 ft/min for 0.001 foot to 6 foot diameter spheres of water. These two estimates are only models of specific cases, but serve to indicate the importance of the sinking rate consideration as a cause of nutrient utilization inefficiency. The experimental results yield sinking rates of 0.42 to 0.15 ft/min, implying that upwelled water might remain in the upper 6 feet of farm for 40 minutes or less.

4.2.2 Current and Wave Motion

Current speeds of several tenths of a knot should be expected in the open ocean, even away from major winds or current systems (82). Surface water flowing into the system will tend to mix with and dilute nutrient-rich upwelled water. Current under the farm and in the deeper (>6 feet of depth) portions of the farm will carry away upwelled water sinking though the upper layer of the farm.

Wave motion in water with depth greater than three wave lengths occurs in vertical circular or orbital paths. This mixing is generally considered to be appreciably felt to a depth of 1/2 wavelength, but considerable evidence exists to show that this is not rigorously correct (83). Waves with very long wavelengths have been reported to mix to greater depths (83). Orbital mixing will tend to dilute nutrient-rich water with deeper water, decreasing the efficiency of nutrient uptake.

The average wavelength in sea state 3 significant waves is 90 feet, and average period 5.1 seconds. Significant orbital mixing might be expected to a depth of 45 feet. Current of 0.3 knots incident to the 100 square mile farm in the top 45 feet is equal to 6,750 gallons per minute per acre (see Appendix D). This is equal to over 6 times the upwelling water flow rate and represents significant nutrient dilution and nutrient utilization inefficiency potential.

From Airy wave theory (83) the amplitude of orbital motion at depth z is given by

$$N_z = N_m \frac{\cosh k(z + d)}{\sinh kd} \qquad 4.1$$

where N_z = amplitude of orbital motion

$N_m = \frac{1}{2} H$ = wave amplitude = 3.05 ft.

H = significant wave height = 6.1 ft.

d = depth of water (bottom to mean water level) = 2,000 ft.

z = depth below water surface.

Table 4.2 gives some values of this parameter for sea state 3 significant waves.

Table 4.2

ORBITAL MOTION AMPLITUDE

(Sea State 3 Significant Waves)

Z	N_z
6	4.0 ft.
10	4.9
20	7.8
30	12.5
45	25.4

4.2.3 Mass Transfer

Mass transfer of nutrients from upwelled nutrient-rich water to plants is the other major heading to be considered. Efficient mass transfer is contingent upon effective distribution of nutrient-rich water throughout the farm. If nutrient-rich water is not evenly distributed, plants in non-enriched areas will not receive requisite nourishment for growth. As discussed in the previous section, rapid sinking of upwelled water could lead to healthy plant growth near distribution pipes but no plant growth only a few feet away. Similar results would be obtained if wave caused mixing diluted upwelled water with nutrient-poor subsurface water, or if current (if any current exists near the surface) flows parallel to distribution pipes.

Another important consideration is turbulent motion of nutrient-rich water around individual plants which would decrease the distance for molecular diffusion (a slow process). Jackson (84) discussed the importance of turbulent mixing on seaweed growth. He notes that Shacklock et al (85) of Waaland (86) found that seaweed growth depended on the degree of stirring in cultures, and Wheeler (87) found a linear relationship between photosynthesis and water velocity for Macrocystis pyrifera. Jackson also states that very large open-ocean systems may behave as closed, land-based systems, with the same mixing, carbon, and other nutrient requirement. The carbon requirement in the open-ocean farm was assumed met by dissolved carbonates in ocean water, but a very large system may inhibit plant growth due to an increase in pH by carbon depletion in the surrounding seawater (84).

Since mass transfer occurs by molecular diffusion, and molecular diffusion is a slow process, the longer nutrients remain in the upper six feet of farm the more efficient will be their utilization. Jackson (84) reports that nutrient uptake rate is given by the Monod equation (88,89):

$$v = \frac{v_m N}{K_s + N} \tag{4.2}$$

where v is the uptake velocity, v_m is the maximum uptake velocity, N is nutrient concentration, and K_s is nutrient concentration when uptake velocity is half of the maximum. Jackson (84) also indicates a biological uptake of

$$\text{biological uptake} = 1-e^{-kt} \tag{4.3}$$

where k is an uptake constant and t is the time after introduction of nutrient to the system. Jackson (84) indicates the uptake constant is approximately 3.9×10^{-3} min^{-1} for nitrate uptake by Macrocystis with a density of 1 kg wet wt per m^3. Thus, for t = 60 min., the biological uptake is 1-0.79 or 21%, while for t = 6 hrs, the uptake is 75% and for t = 12 hrs, it is 94%. Also, in order to obtain 60% uptake, t must be about 4 hrs. Uptake is thus seen to be significantly dependent on residence time.

In summary, factors influencing nutrient utilization include:

- Uniformity of nutrient-rich water distribution
  - Upwelled water sinking rate
  - Mixing and dilution by wave and current action.
- Mass Transfer from nutrient-rich water to plant surface
  - Mixing requirement
  - Diffusion to plant surface
  - Residence time

4.3 Drag Effects in Open-Ocean Systems

Ocean surface currents can extend to a depth of 300 feet, well below the substrate of an open-ocean algae farm. The flow into the leading edge of a 60 foot deep, 10 mile x 10 mile algae farm located in a 1 knot current will be 670,000 gallons per minute. This current is expected to produce a significant effect on nutrient provision and utilization by plants in the farm. The current is also expected to produce considerable drag forces on farm substrate members. Knowledge of drag on the different farm elements is essential for design of farm substrate members.

In order to prevent farm drift with current, the open-ocean algae farm must be anchored or its location controlled by other means. The magnitude of farm drag must be determined to design an anchoring system and to calculate power requirements for the other suggested method of position control, dynamic positioning with propulsors (78).

Ocean current is a location-dependent parameter. It is assumed that the maximum current encountered by an open-ocean energy farm will have a magnitude of 1 knot (1.69 ft/sec). Ocean surface current information specific for location may be obtained from the U.S. Naval Oceanographic Office publication, "Atlas of Surface Currents."

4.3.1 Drag Forces on the Farm

The 100 square mile algae farm can be modelled as a stationary flat plate in a moving fluid (78). In this model the farm is presented as as a solid body, impervious to current at its leading edge, but with water flowing around the bottom and sides. The former effect is referred to as pressure drag while the latter is known as skin friction drag (78). These are the forces which must be overcome to control a farm's position. Wilcox (78) and Budhraja (90) discuss other models for farm drag, but select the flat plate model for analysis.

Wilcox and Budhraja calculate pressure drag by

$$D_p = \frac{1}{2} C_d \rho v^2 A \qquad 4.4$$

where D_p = pressure drag in lb_f

C_d = drag coefficient = 1.17 for the leading edge

ρ = sea water density = 1.99 $slugs/ft^3$

v = current velocity = 1.0 knot = 1.69 ft/sec

A = leading edge area = (60 ft deep) x (length)

This assumption involves the premise that all water incident upon the leading edge of the farm is brought to rest within the farm or displaced beyond the farm's boundaries. Thus C_d is a fixed constant.

The skin friction drag of a solid body is dependent upon the body's length, surface roughness, and the Reynolds Number (Re) of the system. Surface roughness is a function of k, the height of roughness element. Schlichting (91) correlates the parameter k with the skin friction drag coefficient, C_{sf}, by means of k_s, the height of grain for equivalent sand roughness. Wilcox (78) estimates that k_s probably lies between 0.1 and 10 ft. Theoretical minimum and maximum skin friction drag values are obtained when k is equal to the "admissable roughness" (k_{adm}), the maximum height of protuberances from a solid body which do not increase drag above that found in a perfectly smooth solid body, and 60 ft., the height of kelp from holdfast to surface, respectively.

Schlichting(91) presents correlations for C_{sf} for both laminar and turbulent flow past a flat plate as a function of $1/k_s$ and Re. Turbulence begins at Reynolds Numbers of approximately 10^5, and is fully developed at Re > 5 x 10^5 for a flat plate. The Reynolds Number for flow past a flat plate is defined as

$$Re = \frac{vl}{\nu} \qquad 4.5$$

where v = current velocity

l = length of plate

ν = seawater kinematic viscosity = 1.66×10^{-5} ft^2/sec.

For a current velocity of 1 knot (1.69 ft/sec)

$$v/\nu = 1 \times 10^5$$

so that turbulent flow is expected over the entire length of the farm.

The expression presented by Schlichting (91) for the skin friction drag coefficient in turbulent flow as a function of l/k_s for values of l/k_s between 10^2 and 10^6 is

$$C_{sf} = (1.89 + 1.62 \log_{10} (l/k_s))^{-2.5} \qquad 4.6$$

where C_{sf} is defined as

$$C_{sf} = \frac{D_{sf}}{\frac{1}{2} \rho v^2 A} \qquad 4.7$$

with D_{sf} = skin friction drag in lb_f

ρ = water density = 1.99 slugs/ft^3

v = current velocity in ft/sec.

A = surface area in ft^2

ρ = farm length

k_s = height of grain for equivalent sand roughness

Therefore the total skin friction coefficient for a farm can be calculated by assuming a value for k_s, and the total farm skin friction drag can be calculated from the definition of skin friction drag

$$D_{sf} = \frac{1}{2} C_{sf} \rho v^2 A$$

Figure 4.1 graphically presents the relation between C_{sf} and $1/k_s$ and k_s for the single module 100 square mile farm.

Schlichting also gives the relation

$$k_{adm} \leq 100 \frac{\nu}{u_\infty}$$

as the admissible protuberance height for smooth surfaces. This $k_{adm} \leq 9.8 \times 10^4$ ft. for ν of seawater and $U_\infty = 1$ knot. The value of C_{sf} for smooth surfaces (91) are included for comparison in Table 4.3, which presents the total skin friction coefficient, pressure drag force, skin friction drag force, and total drag forces for various 100 sq. mile algae farm system configurations ranging from 100 modules of one square mile size to one module of 100 square mile size.

A local skin friction coefficient C'_{sf} is also defined by Schlichting, based on the distance Reynolds Number, $Re = \frac{U_\infty x}{\nu}$, where U_∞ and ν are as previously defined and x = distance from the leading edge.

This parameter is necessary to calculate forces acting on the farm at various distances from the farm leading edges, for example, ropes on leading edges of the farm will undergo more stress than ropes in the center (78). Schlichting correlates this coefficient with 1/ks by the relation

Figure 4.1

Total Skin Friction Coefficient for Various k_s

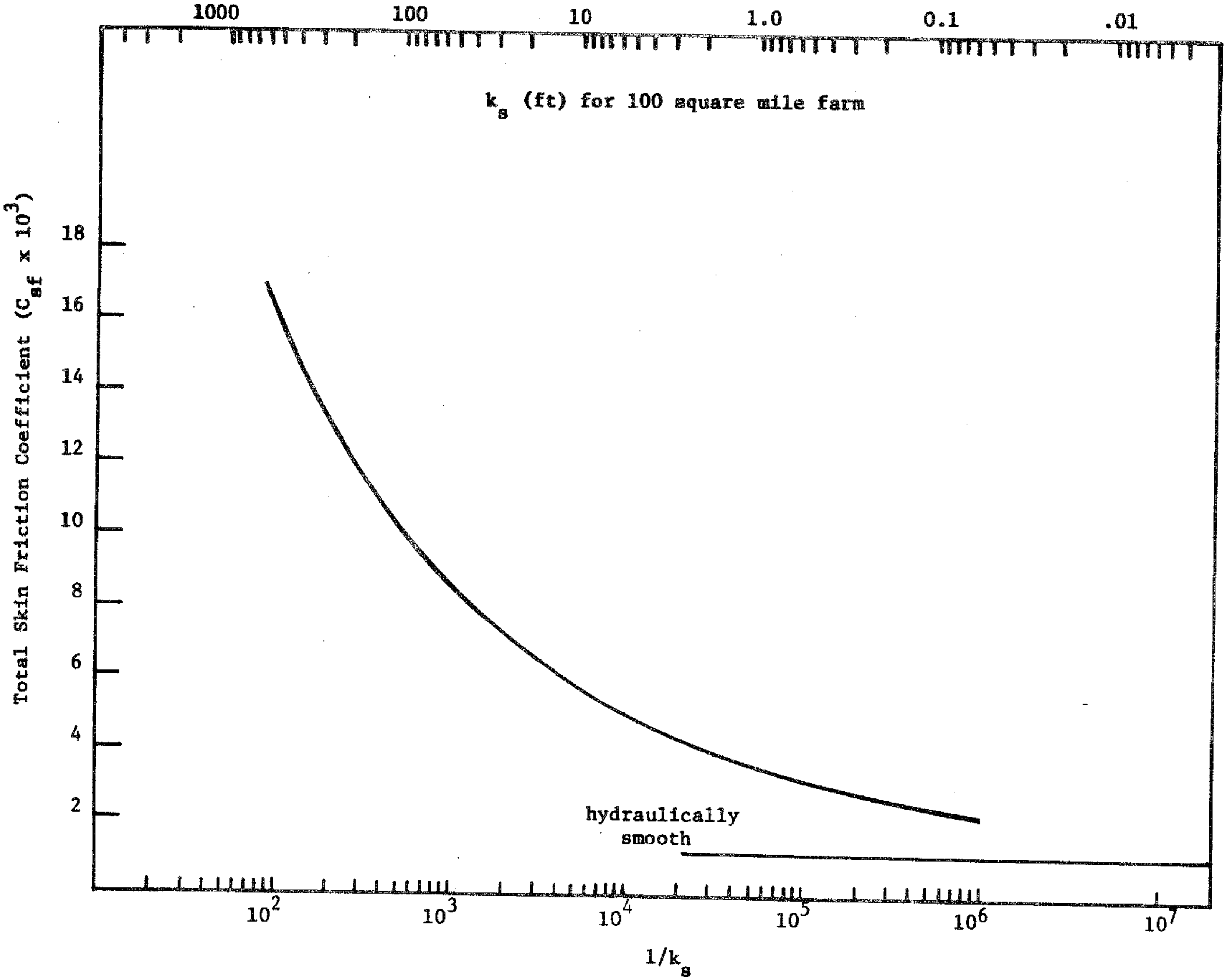


Table 4.3

FARM DRAG

Modules	Area/Module mi^2	Parameter	$k_s = 0.1$	$k_s = 1.0$	$k_s = 10$	$k_s = 60$	Hydraulically Smooth C_{sf}	Range of Skin Drag Per Module (k_s = 0.1 to 10) lb_f	Range of Total Skin Drag (k_s = 0.1 to 10) lb_f	Pressure Drag Per Module lb_f	Total Pressure Drag lb_f	Range of Total Drag lb_f
100	1	$1/k_s$	5.3×10^4	5.3×10^3	5.3×10^2	88		2.8×10^5 to	28.5×10^6 to			133×10^6 to
		C_{sf}	3.6×10^{-3}	5.7×10^{-3}	10×10^{-3}	18×10^{-3}	1.7×10^{-3}	7.92×10^5	79.2×10^6	1.05×10^6	105×10^6	185×10^6
10	10	$1/k_s$	1.7×10^5	1.7×10^4	1.7×10^3	280		2.3×10^6 to	23.0×10^6 to			56.2×10^6 to
		C_{sf}	2.9×10^{-3}	4.4×10^{-3}	7.4×10^{-3}	12.1×10^{-3}	1.5×10^{-3}	5.86×10^6	58.6×10^6	3.32×10^6	33.2×10^6	91.8×10^6
5	20	$1/k_s$	2.4×10^5	2.4×10^4	2.4×10^3	390		4.27×10^6 to	21.4×10^6 to			45.0×10^6 to
		C_{sf}	2.7×10^{-3}	4.1×10^{-3}	6.8×10^{-3}	10.9×10^{-3}	1.4×10^{-3}	10.8×10^6	53.8×10^6	4.71×10^6	23.6×10^6	77.4×10^6
2	50	$1/k_s$	3.7×10^5	3.7×10^4	3.7×10^3	620		9.88×10^6 to	19.8×10^6 to			34.7×10^6 to
		C_{sf}	2.5×10^{-3}	3.8×10^{-3}	6.1×10^{-3}	9.6×10^{-3}	1.3×10^{-3}	24.1×10^6	48.2×10^6	7.45×10^6	14.9×10^6	62.9×10^6
1	100	$1/k_s$	5.3×10^5	5.3×10^4	5.3×10^3	880		1.9×10^7 to	19.0×10^6			29.0×10^6 to
		C_{sf}	2.4×10^{-3}	3.6×10^{-3}	5.7×10^{-3}	8.7×10^{-3}	1.3×10^{-3}	4.5×10^7	45.2×10^6	10.5×10^6	10.5×10^6	55.7×10^6

$$C'_{sf} = (2.87 + 1.58 \log_{10} \frac{x}{k_s})^{-2.5}, \qquad 4.8$$

again valid for $10^2 < \frac{x}{k_s} < 10^6$.

Local skin friction coefficients for various k_s and x values and for smooth surfaces ($k < k_{adm}$) are listed in Table 4.4. Figure 4.2 graphically presents the relation between the local skin friction coefficient and the distance from the leading edge for the k_s range of 0.1 to 60, and for an hydraulically smooth surface. The most probable range of $0.1 < k_s < 10$ is cross hatched in Figure 4.2. Local drag force calculations are developed in detail by Budhraja in Reference (78), and are suitable for specific farm substrate member design.

The total drag on a farm is presented in Figure 4.3 as a function of farm module size. It is noted that as the farm module size decreases, the effect is to significantly increase the total drag on the 100 square miles of farm. The result would be to increase the size and hence the cost of substrate lines and mooring lines.

The values for total farm drag obtained here may be compared to the values reported by Wilcox and Budhraja for 100,000-acre farm (12.5-mile-long sides) of 75.66×10^6 lb_f and 61.3×10^6 lb_f respectively. These are equivalent to 48.4×10^6 lb_f and 39.2×10^6 lb_f for the 64,000 acre farm discussed in this analysis. The analysis presented here yields a range of 29.0×10^6 to 55.7×10^6 lb_f, encompassing the previous estimates and displaying good agreement with them.

Figure 4.2

Local Skin Friction Coefficient vs. Farm Length

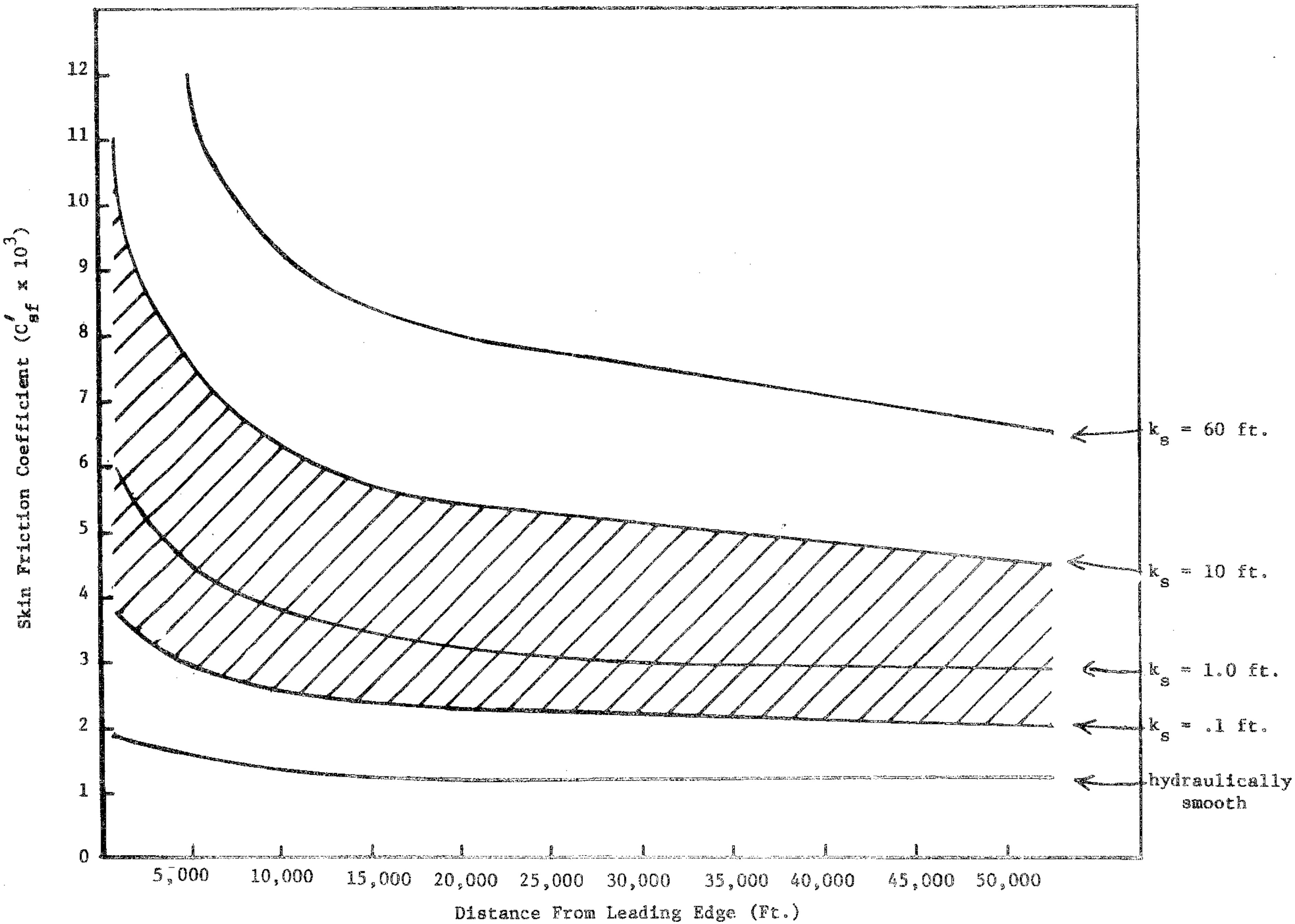


Figure 4.3 Total Drag vs. Farm Module Area

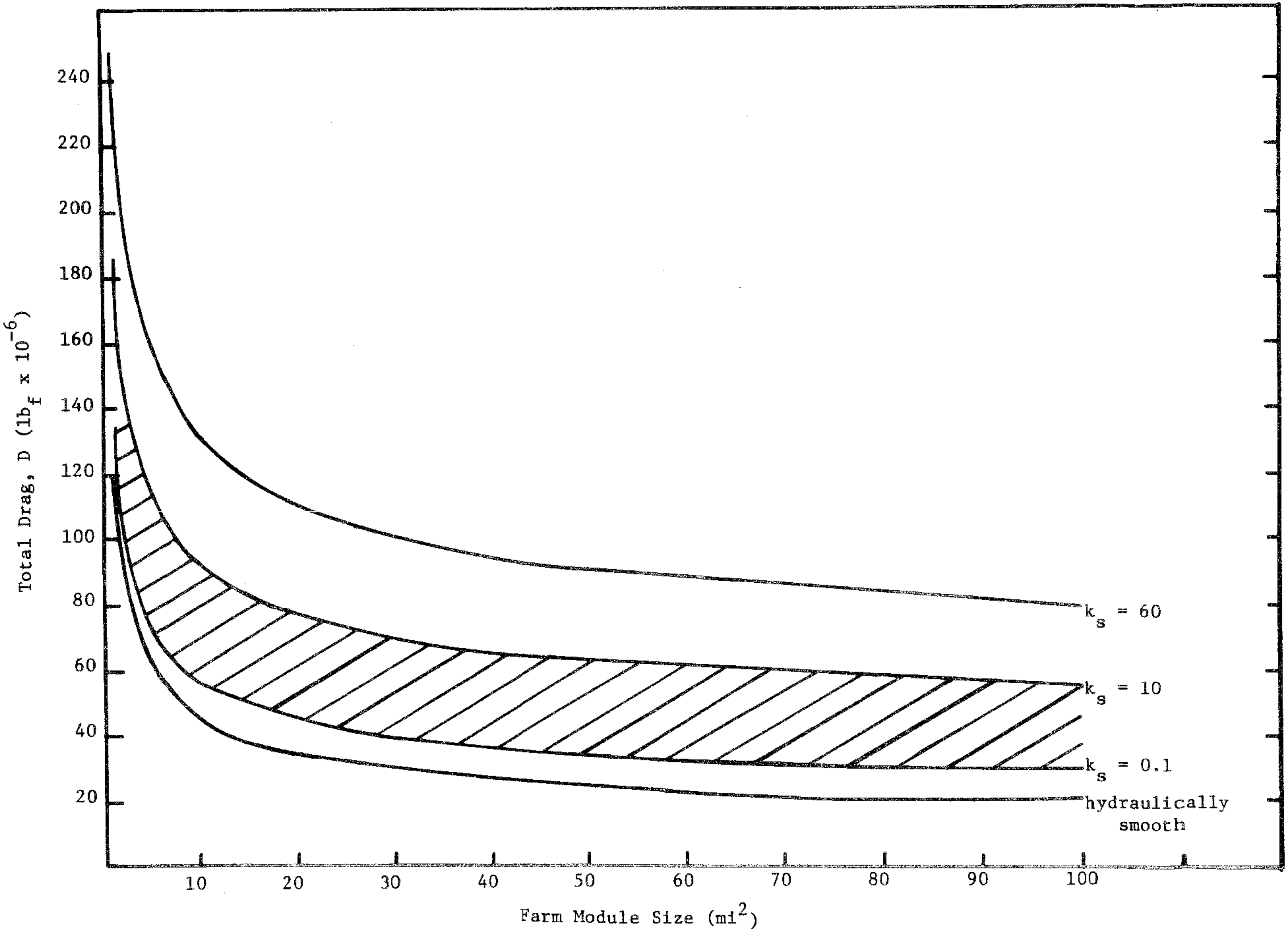


Table 4.4

LOCAL SKIN FRICTION COEFFICIENT

x(ft)	1,000	5,000	10,000	15,000	20,000	52,800
$Re_x = \frac{U_\infty x}{\nu}$	1.0×10^8	5.1×10^8	1.0×10^9	1.5×10^9	2×10^9	5.4×10^9
Hydraul. smooth	1.9×10^{-3}	1.6×10^{-3}	1.4×10^{-3}	1.3×10^{-3}	1.25×10^{-3}	1.2×10^{-3}
$k_s = 0.1$	3.9×10^{-3}	2.94×10^{-3}	2.6×10^{-3}	2.5×10^{-3}	2.4×10^{-3}	2.04×10^{-3}
$k_s = 1.0$	6.3×10^{-3}	4.5×10^{-3}	3.9×10^{-3}	3.6×10^{-3}	3.4×10^{-3}	2.9×10^{-3}
$k_s = 10.0$	11.2×10^{-3}	7.4×10^{-3}	6.3×10^{-3}	5.7×10^{-3}	5.4×10^{-3}	4.4×10^{-3}
$k_s = 60$	---	11.8×10^{-3}	9.7×10^{-3}	8.7×10^{-3}	8.1×10^{-3}	6.4×10^{-3}

4.4 Carbon Dioxide Transfer Considerations

4.4.1 Introduction

The component which must be transferred in largest quantity to the growing biomass is carbon, which must be made available as carbon dioxide. CO_2 sources may be either atmospheric air, or other enriched sources such as power plant stack gas. Transfer considerations vary depending on both the CO_2 source, and whether biomass if floating or submerged.

4.4.2 CO_2 Transfer to Submerged Microalgae

4.4.2.1 General Considerations

A number of investigators have proposed the growth of submerged biomass for conversion to fuels; some discussion, including realistic assessments of drawbacks, is contained, for example, in the literature (76, 77).

For submerged microalgae, it may be readily established that CO_2 diffusion from the liquid bulk to the algae is unlikely to limit the circumstances of interest. (This is true for all other nutrients.) The major diffusional limitation, whatever the transfer method chosen, will be in the liquid film on the liquid side of the gas-liquid interface. In this case, the governing equation is:

$$\dot{R} = \frac{k_\ell a}{v} (C^* - C) \qquad (4.9)$$

		Units
where:	$\dot{R}$ = mass transfer rate	$ML^{-3}t^{-1}$
	k_ℓ = liquid-side mass transfer coefficient	Lt^{-1}
	a/v = area of interface per unit volume	L^{-1}
	C^* = equilibrium concentration of dissolved gas at interface	ML^{-3}
	C = concentration of gas in liquid bulk	ML^{-3}

where units are: M = mass L = length t = time

It is common in the fermentation industry to express $k_\ell a$ in units of mmols/l·hr·atm. This will be the convention here.

4.4.2.2 CO_2 Transfer to Submerged Biomass by Sparging Atmospheric Air

The first case considered is use of atmospheric air as a CO_2 source. While little information is available on CO_2 transfer *per se* in systems to be considered, there are well-established mass transfer correlations for oxygen in similar systems. A straightforward adaptation of these oxygen transfer correlations (92) may be carried out:

$$\frac{k_\ell(CO_2)}{k_\ell(O_2)} = \frac{s_{CO_2}}{s_{O_2}} \left(\frac{D_{\ell,CO_2}}{D_{\ell,O_2}}\right)^{2/3} \qquad (4.10)$$

where: s = gas solubility, mmols/l·atm

D_ℓ = gas diffusion coefficient in liquid

Values for solubility of CO_2 and O_2 in aqueous water at 20°C are shown in Table 4.5. Substitution of these values shows that for a given activity gradient in atmospheres, the rate of CO_2 transfer will be about 20 times that for O_2 where $k_\ell a$ is expressed in units of mmols/l·hr·atm.

Sparging is one option which may be considered to supply CO_2 with atmospheric air. For the idealized case, tranfer per unit energy expenditure is maximized when stripping is minimal, e.g., when the gas phase concentration of CO_2 stays near 330 PPM. (This situation is obtained with a shallow diffuser or sparger.) Results of the net energy computation (see Appendix D for details) are shown in Table 4.6., which shows energetics to be unfavorable. Though transfer might be augmented by various means, such as increasing alkalinity or the application of more esoteric and capital intensive equipment than spargers, (for example, gas-lift transfer stations), the conclusion is that the energetics of sparging would remain unfavorable. (Without going into detail, it will be noted that energetics of such methods as transfer by surface aerators will be even less favorable.)

Table 4.5

Solubility and Diffusivity of CO_2 and O_2 in Water at 20°C

	Solubility, mmol/l·atm	Diffusivity, cm^2/sec
O_2	1.38	2.28×10^{-5}
CO_2	29.1	1.77×10^{-5}

Table 4.6

Summary of Net Energetics for Sparging Atmospheric Air to Provide CO_2

Sparging PV work to transfer 1 lb C > 1.7×10^5 BTU/lb
Gross Energy Available/lb C = 1.77×10^4 BTU/lb

Energy consumed/Energy produced > 10, i.e., ratio is highly unfavorable.

Assumption: Driving force = 3.3×10^{-4} atm (Zero concentration in liquid phase, minimum stripping, ideal case). See text and Appendix D for further details.

4.4.2.3 CO_2 Transfer to Submerged Algae by Passive Diffusion from Atmospheric Air

The adequacy of CO_2 uptake with passive diffusion may be considered. This uptake is simply that arising in the normal course of events from atmospheric CO_2 diffusion through the surface of the water body in the presence of the activity gradient from atmosphere to the water. Here, adaptations of extant oxygen transfer correlations to CO_2 uptake (as discussed in Appendix D, and later in Section 4) show estimated uptake rates of 70 to 7000 lb/acre•year. These are insufficient to support baseline growth. This estimate is based on the maximum possible activity gradient of 3.3×10^{-4} atm. CO_2 driving force; in lesser gradients uptake would be less. Thus reliance on passive diffusion to supply necessary CO_2 from atmospheric air to submerged growth systems appears impractical.

4.4.3 Use of Power Plant Stack Gas a a CO_2 Source

The foregoing problems with use of atmospheric air as a CO_2 source are due to the fact that the maximum possible CO_2 activity gradient for transfer is 3.3×10^{-4} atmospheres. A number of investigators have proposed the use of power plant stack gas a CO_2 source. The CO_2 content of stack gas runs 7 - 15% and 10% will be assumed for purposes of this analysis. The driving force available for mass transfer is over two orders of magnitude higher than that with atmospheric air.

Three factors must be considered initially in the design of a system to deliver CO_2 from power plant stack gas to a submerged biomass growth system. First, CO_2 must be delivered at a large number of points within the system. If added at only a few points within the system at large local excess, it will mostly desorb before assimilation. A discussion of practical transfer station spacing is presented in Appendix 4.2. Secondly, because of capital cost associated with the distribution network (discussed later) fractional CO_2 absorption must be high for best economics (e.g., most efficient use of capital). Finally, the piping system must be designed to deliver CO_2 not at the average system requirement, but to meet peak needs at maximum photosynthetic rates, during peak sunlight, as noted in Appendix D.

As the basis for design computations it will be assumed that fractional absorption of CO_2 at sparger stations is 75%. A further assumption is that loss between transfer stations is $\sim$ 25% of the CO_2 absorbed into the system. (These conditions are not necessarily optimal.)

With these assumptions it can be computed that the necessary head for 75% CO_2 transfer is about ten feet and the energy expenditure to transfer the CO_2 will be about 10% of GEO at the assumed 30% thermal to mechanical conversion efficiency. This is for the sparging step alone. Thus a significant energy drain is imposed even in transferring CO_2 from a relatively enriched source such as power plant stack gas.

It is worthwhile here to also take a look at characteristics of the distribution system necessary to enable stack gas CO_2 use. The assumption is made here that pumping work for CO_2 delivery from generating station to the farm must not exceed 2% of G.E.O., of which loss 1% is in the main distribution system and 1% in the header. This constraint imposes a maximum allowable pressure drop of 150 lbf/ft^2. If the main pipe bringing CO_2 from the power plant site is 10 miles long, then the minimum diameter may be established to be 30 ft. (50,000 CFS of stack gas will be needed to meet a peak need 5 times the average). Extant guides to pipe costs suggest a cost of 25 to 50 million dollars for the pipe and associated trench alone (93).

The distribution network presents a somewhat more difficult evaluation because of the uncertainty in spacing of transfer stations. As noted in Appendix D this spacing could vary between 10^3 and 10^5 feet. However, a main delivery header will be required along one side of the farm, whose cost, depending on configuration, will be in the order of \$10 - 30 million dollars. Additionally, costs have been estimated for a piping configuration suitable for a 2,000 feet spacing between transfer stations. The simplest piping arrangement to provide CO_2 to a multiple parallel channel arrangement with this spacing is a series of 26 pipes, perpendicular to channel flow. These will taper downward from 6' diameter, and each will be 10 miles long. (They must at minimum traverse the farm.) These pipes must be installed in trenches below maximum water depth so as not to impede necessary water flow. With excavation added the cost is estimated at \$30 - \$60 million. The previous piping costs add up to approximately \$100 million for piping and installation alone, for one 100 mi^2 farm, or about \$1600/acre. Thus while use of CO_2 from stack gas is not totally out of the question, it will pose a serious energy drain (about 12% of GEO by this estimate), and presents high capital costs as well. The expense could be reduced if the power plant could be located next to the farm, in which case the capital cost would be solely that cited for the header and distribution system.

Note also that the distribution system cost estimate excludes any costs for scrubbing, which might be necessary to remove components corrosive to the pipe or toxic to the biomass. Based on extant costs for stack-gas scrubbing to meet air quality standards (e.g., 1.2 lb SO_2/mm BTU), for power plants it is probable that these could be a significant increment. Likewise, condensate taps have not been included, and neither has the cost for spargers.

Passive transfer of CO_2 from power plant stack gas is a possibility; preliminary calculations (following the method of O_2 uptake computation in Section 4.5.3) indicate that 75-90% of the stack gas CO_2 could be transferred with bubble covers whose areal fraction can be estimated roughly at 0.5 to 5% of the total liquid surface. Net energetics would be expected to be greatly improved relative to sparging. This possibility needs more investigation.

4.4.4 Carbon Dioxide Transfer to Floating Plants

The preceding discussion in Sections 4.4.2 and 4.4.3 indicates that CO_2 transfer to any submerged biomass is likely to present problems, whatever method is chosen. It is of interest to examine the carbon dioxide transfer situation with floating plants where a portion of the biomass is above water.

A rather simple and straightforward order-of-magnitude approximation of the ratio of CO_2 transfer coefficients to surfaces in air and water is given by the product of the ratio of diffusivities of CO_2 in air and water with the ratio of partition coefficients. A further factor which must be considered is that the area of exposed biomass surface over water will not in general be equal to the water surface, and compensation must be made for this area ratio. Thus,

$$\frac{N_{T_{air}}}{N_{T_{water}}} \approx \frac{1.4 \times 10^{-1}}{1.77 \times 10^{-5}} \times \frac{1}{.878} \times \text{Area ratio} \qquad (4.11)$$

where: $N_{T_{air}}$ = Transfer rate to plants floating over unit water area

$N_{T_{water}}$ = Transfer rate obtaining per unit water area

and the ratios of diffusion coefficient and the partition coefficient are shown (at 20°C = 68°F).

The ratio of plant leaf area to water area over which it stands can easily exceed 1.0. Thus on this basis the expected carbon dioxide uptake by above-water plant surface would be expected to be a factor of 10^3 to 10^4 greater than the uptake of the water surface beneath it for a given activity gradient. Multiplying previous results for carbon dioxide trnasfer to water by this value for the transfer ratio gives carbon dioxide transfer rates almost certainly adequate to meet system needs.

A factor not considered is that hydraulics of air and water transport differ and this will also affect the magnitude of the film coefficient. However a computation in Appendix D using a somewhat different approach shows results which do not alter the conclusion presented. Thus it is seen that emersed (floating) plants largely, if not completely, overcome the CO_2 transfer problems associated with submerged systems. (Note that this analysis considers only diffusional limitations and not types of concentration effects on growth rates and growth which would occur from Monod kinetics. Increased CO_2 around the plants could improve growth, not because diffusion is augmented, but for other kinetic reasons implicit in the Monod and similar models.)

4.5 Nutrient Requirements and Effect of Recycle on Nutrient Requirements

The baseline conditions for a 100 square mile land-based farm, result in a nutrient requirement of 19,200 tons/yr of nitrogen and 1920 tons/yr of phosphorus. The figures assume that nutrients required to meet plant requirements are supplied and then lost. The nutrient needs could be met by chemical fertilizer. Alternatively, many investigators have advocated the use of sewage for nutrients. Phosphorus is ample in sewage, and based on sewage nitrogen content, a city of 5 million would be required to supply nitrogen for one farm. Another option is the use of upwelled ocean water as has been considered for open ocean systems. Finally, it is possible that nitorgen needs could be met by its fixation from atmospheric air.

It is worthwhile to comment on energetics and logistics of each of these options. The energy requirement to manufacture one ton of anhydrous ammonia is well-established at 37×10^6 BTU/ton ammonia, corresponding to 45×10^6 BTU/ton nitrogen. The manufacture of ammonia alone imposes an energy requirement of 8.6% of the gross product heating value, or 17% of the net. If chemical fertilizer were used on a "once through" basis this would be a major energetic drain. With sewage, the likelihood that one city of five million would be available and in the right location to meet the needs of one 100 mi^2 system, let alone many, is small. With deep ocean upwelling, a severe energetic cost is imposed by pumping head losses; to provide necessary nutrients an energy consumption equal to 4% of G.E.O. occurs for each foot of pumping head. Additionally, a pipe must be installed to bring in the deep ocean water. It is unlikely that the length of the pipe would be less than 10 miles. To assure that pumping losses are not unreasonable the diameter would need to be in excess of 100 feet. Installation of such a pipe in deep ocean waters is not feasible with present engineering techniques, and if such installation were to become so it is likely that cost would be astronomical. Some microalgae (such as Azolla) can fix nitrogen directly from atmospheric air. It might be practical to utilize such algae to avoid nitrogen addition entirely, but the energetics of such fixation (6 ATP/atom N) suggest that fixation might be accomplished at the expense of some decrement in yield.

The above discussion pertaining to "once through" use of fertilizer indicates that chemical fertilizer provision imposes a severe energy drain and with the exception of fixation other methods are impractical. If it is possible to "close the cycle", utilizing a conversion method which conserves nutrients and allows their re-use, nutrient needs will become more reasonable. As an example, if 90% of nutrients contained in product biomass were conserved and returned to the growth process, nitrogen requirement would be $\sim$ 1900 tons/yr and phosphorus, $\sim$ 190 tons/yr. Fertilizer use (anhydrous ammonia) becomes quite practical in this case on an energetic basis, consuming less than 1% of G.E.O. for its manufacture. (The fertilizer cost component at current market, $\sim$ 180/ton NH_3, would be about 5¢/mmBTU G.E.O.) Sewage from a city of 500,000 would supply one 100 mi^2 farm, and it is possible that several such farms could derive their nutrients from this source. Credits could apply in this case. Upwelling of deep ocean water for land based systems (calculations not shown) remains impractical with 90% nutrient recycle; the piping diameter remains in excess of 50 feet and severe constraints remain as with once-through use.

Thus, nutrient recycle is seen to be highly desirable, and feasibility of one possible recycle approach will be discussed in a later section.

4.5.1 Nutrient Concentration and Nutrient Mass Transfer Considerations

The purpose here will be to determine a practical nutrient concentration and to evaluate possible constraints on concentration. Nutrient concentrations in land-based aquatic biomass growth systems must be high enough to meet system needs with a practical flow configuration, minimizing the number of addition points. Concentration must also be high enough so that mass transfer to the biomass is adequate under likely hydraulic conditions. At the same time, concentration cannot be so high that, for example, leaching losses are great enough to preclude high fractional recycle.

A choice of conditions is made here in order to determine whether a combination of nutrient concentration and other system parameters is reasonable.

If one such system combination is reasonable, and safety factors are large, it can be assumed that other combinations of nutrient concentrations and system parameters such as flow rates, etc., will also be practical.

The assumption is made here that a system having a water depth of 3 feet is supplied with nitrogen* at a concentration of 1.0 PPM, or 10^{-3} gram/liter. Under baseline conditions, this nutrient level would satisfy the system needs for 7.5 days. As will be demonstrated later, this hydraulic residence time (or, alternatively, circulation time) is reasonable.

An important criterion for practicality of this nutrient level is that mass transfer rates are adequate to the biomass under hydraulic flow conditions which are also reasonable. A choice of biomass must be made for purposes of evaluation, and the choice here is water hyacinth, for which some of the necessary values are known. Relevant characteristics of water hyacinth are shown in Table 4.7 (94). Published values are not available for root diameters, and fluid velocities with the current state of knowledge must be considered somewhat indeterminate; a one-order-of-magnitude estimate for a reasonable range to assign each of these parameters is shown in Table 4.8.

A mass transfer coefficient may be readily computed (92). The choice of parameters gives a range of values for the product of the mass transfer coefficient and the area, shown for each of the four possible combinations of lower and upper bounds of fluid velocity and root diameter in Table 4.8. The computations are based on one dry kilogram of standing biomass per square meter, about a five month crop under baseline conditions. A conservative estimate of the nitrogen requirement may be made, assuming that the peak uptake rate is five times the year-round average, as ~ 1 gm/m^{2}day. The lowest possible mass transfer coefficient-areal combination, (assuming Δc = 1 mg/l) gives a potential uptake rate of 10 gm/m^{2}day and all other cases give uptake rates which are even greater. For this particular system mass transfer will be ample, and the safety factor is large. It is evident

*The identical arguments to be made here apply to phosphorus, whose discussion is omitted for simplicity.

Table 4.7

Characteristics of Water Hyacinth and Other Assumptions Used in Computing Mass Transfer Rates to Water Hyacinth Roots (94)

Standing biomass crop = 1 kg/m^2

Fraction of dry biomass in roots = 25%

Fraction of water in total biomass = 95%
(e.g., wet weight is 5% solids)

Root mass (wet) = 5 $kg/m^2 \approx 5000\ cm^3$

For root mass = 5 kg/m^2:

1 mm dia	Area = $2 \times 10^5\ cm^2/m^2$
0.1 mm dia	Area = $2 \times 10^6\ cm^2/m^2$

Table 4.8

Computation of Mass Transfer Coefficient and Nutrient Uptake for Combinations of Water Hyacinth Root Diameter and Water Velocity Past Roots

Root Diameter, cm	Water Velocity Past Root, cm/sec	k_ℓ, (1) cm/sec	$k_\ell a\Delta c$, (2) gm/m$^2\cdot$day
0.1	0.1	7.52×10^{-4}	13
0.1	1.0	1.94×10^{-3}	34
0.01	0.1	3.74×10^{-3}	650
0.01	1.0	7.52×10^{-3}	1300

(1) $k_\ell = 2D_\ell/D\left[1 + .276\ Re^{1/2}\ (\mu/\rho D_\ell)^{1/3}\right]$, Ref.

(2) at $\Delta c = 1$ mg/l $= 10^{-6}$ gm/ml

NOTE: The time-average uptake required (24 hr/day, 365 days/yr) is .184 gm N/m$^2\cdot$day; the minimum uptake rate computed above allows a large safety factor, even if nutrient needs peak during the day at a sevenfold multiple of the average rate.

that this favorable situation is likely to hold with other biomass species as well as water hyacinth.

It is worth noting, also, that nutrients may be stripped, if necessary, from the exit water bleed stream. These computations are presented in Appendix D. Thus pollution through release of nutrients from the farm can be avoided with proper configuration of the outflow.

4.5.2 Feasibility of Nutrient Recycle

A number of conversion processes may be utilized to convert biomass to product, which (in addition to burning, where the product is heat) can be divided into the categories of thermochemical and biological conversion to fuel. Thermochemical processes will have distinct disadvantages for nutrient recycle since a substantial fraction of organically bound and ammonia nitrogen in the feedstock biomass will be lost as molecular nitrogen. (Phosphorus and minerals will be conserved.) In addition, the remainder of nitrogen, in the form of either ammonia or NO_x would likely require expensive separation. A bioconversion process, on the other hand, will produce a mixed liquid-solid residue in which the original input nutrients are quantitatively conserved (see Appendix D) and near-quantitative retention is necessary for the high fractional nutrient recycle postulated in Section 4.5.1.

The residual product of any biological conversion process will contain not only free but also organically bound nutrients. Chemical processing techniques to release bound nutrient are expected to be prohibitively energy-intensive, and expensive. The residue may, however, be processed biologically. If such processing is carried out aerobically to the extent that carbon utilization is near-complete, then fractional nutrient release (the nutrient of concern here is nitrogen) may be expected to be high enough that the fractional nutrient recycles postulated in 4.5.1 can be obtained. (A discussion of some of the factors bearing on nutrient recycle by aerobic processing, and unknowns, is presented in Appendix D.)

To carry out this aerobic processing, the oxygen demand of the residue from the conversion step must be met; to compute this oxygen demand some assumptions must be made about conversion. With net product energy yield of 50% assumed from the conversion process, some additional energy will be consumed to meet internal process requirements, and the rest of the energetic content of the initial biomass feed will appear as its equivalent in BOD. It will be assumed here that internal process energy consumption (in addition to, not subtracted from, the net energy output) is 1/3 of the net energy output, or 1/6 of the gross. Thus 1/3 of the original BOD in the biomass substrate will remain for aerobic utilization. Assuming 100 kcal/g·mol O_2 utilized (e.g. 180 KBTU/lb mol O_2 used and working on the basis of heating value) the oxygen demand of the residue may be readily computed to be about 60 lb/10^6 BTU of G.E.O. Provision of the mechanical work necessary to transfer this oxygen would require 13% of the G.E.O., or $\sim$25% of the net (Appendix D). This energy demand is such that this option is at best marginally practical.

It is of interest to review the case where the liquid/solid residue is simply reintroduced into the growth system. In this case, the question is whether passive aeration taking place in the normal course of events is sufficient to allow aerobic re-utilization of the material. If practical, this approach would have a large advantage relative to other possible approaches in that the incremental energy requirements would be close to nil. The incremental equipment cost would also be small, in the limit, the cost of a pipe or pipes to carry effluent from the conversion plant to appropriate injection points.

The question is, then, whether the magnitude of likely surface aeration is sufficient to allow aerobic nutrient release and utilization with this approach. An excellent review paper (95) summarizes results by 17 different workers and tests combined data of all workers against the individual aeration correlations of each investigator. The best predictor of re-aeration rates was found to be that of Parkhurst and Pomeroy (96). Though assembled data center on the correlation, scatter is a factor of 10 in either direction relative to the prediction (see Appendix D and Ref. 96).

The correlation may be applied to compute an uptake rate for oxygen; for purposes of computation a fluid velocity of 5 cm/sec (0.17 ft/sec) is assumed. As demonstrated later, this flow rate is reasonable and meets all other identifiable constraints.

The computed uptake rate (Appendix D) is 6 - 600 x 10^4 lb/acre year in the idealized case where the activity gradient across the gas-liquid interface is 0.21 atm. This result applies to an open liquid surface. A further adjustment must be made for fractional surface coverage when floating plants are present. This fractional coverage can be defined as the areal fraction of a gas-liquid interface occupied by plant material rising through the surface (e.g., the fractional area occupied by plant at the plane of the gas-liquid interface. It is to be noted that this is not the projected horizontal area of leaves in the system, which will be higher.) If it is assumed that the areal fraction ranges between 1/4 and 3/4, then a simple multiplication yields a probable range for oxygen uptake in the ideal case of 1.5 x 10^3 to as much as 4.5 x 10^5 lb/acre year. This range indicates that nutrient recycle, might be practical and economic, with simple reintroduction of conversion process effluent into the farm. This is an area requiring further investigation.

4.5.3 Upwelling for Open Ocean Farms

The three primary elements which must be provided for plant growth are carbon, nitrogen, and phosphorus. One possible source of nutrients is upwelling deep ocean water which has significantly greater nutrient concentrations than is present in surface water. This fact, plus the economic and energetic expense of purchased nutrients and the infeasibility of nutrient recycle in the open ocean indicates that upwelling is the most feasible fertilization technique. In the following analysis, it is therefore assumed that nutrients are provided by upwelling and the system design calculations are made assuming that nitrogen is the limiting nutrient.

4.5.3.1 Upwelling Requirements

The amount of upwelled water required to provide nutrients for growth is presented in Table 5.7 for design assumptions of 1.6% plant nitrogen, 25 μgA/l nitrogen concentration in upwelled water, and 30 - 60% nutrient utilization. Any variations from these conditions would result in easily calculated changes in upwelling requirements.

4.5.3.2 Power Requirement

The design criteria include an assumed 4.8 ft (H_2O) pressure head loss for upwelling and distribution density and friction losses. The power required to upwell and distribute is:

$$\text{Power} = \Delta P \cdot Q \tag{4.12}$$

If upwelling were provided by a fuel or electric driven pump, an over-all fuel to mechanical energy conversion efficiency would have to be included. For an axial flow pump, an efficiency of 80% is reasonable (97). This must be combined with a fuel engine efficiency of 30% to give an over-all efficiency of about 25%. Thus, for a yield of 10%/A•yr, 60% nutrient utilization, and 25% pumping efficiency, the power requirement for upwelling is about 2 hp per acre. This is about 30% of the gross energy output of the farm. Since upwelling power requirement and gross energy output are both directly proportional to algal yield, this energy utilization percentage of 30% is also independent of yield. Also, for a nutrient utilization of 30%, twice the upwelling flow is required and hence twice the power is needed. This then results in 60% energy utilization for upwelling. As nutrient utilization efficiency decreases, a point will be reached where upwelling energy required is large enough to make net farm energy production unattractive economically or energetically. At this point, some form of "free" energy (such as wave power) must be employed for upwelling in order to favorably influence the farm energy or economic balance. This removes the upwelling and distribution power requirement as a farm operating expense.

4.5.3.3 Wave Power

Utilization of wave power has been suggested as a means of powering deep sea water upwelling. Wind-generated ocean waves contain a significant amount of energy (81). Converted to a form suitable for water upwelling, a major farm energy requirement could be fulfilled by using a "free" energy source, wave power, if sufficient wave power were available.

Open ocean waves occur with a large range of heights, wave lengths, and frequencies (83). Small surface waves are caused primarily by wind force on the ocean surface (83). Wind generated waves in deep water can be defined by a spectrum composed of the individual wave components. Since wind actions are essentially random, wind generated waves also move at random. These random motions can be described by a Rayleigh probability distribution (83) and an average wave height and average wave period can be defined from this spectrum. Surface waves are most commonly described in terms of significant wave height, which is defined as the average height of the highest third of waves (83).

The amount of power contained in ocean waves has been computed in various ways by numerous individuals. Pierson and Salfi (98) report that wave power can be computed from the wave height and period data by means of the formula:

$$\frac{\text{Power}}{\text{ft waterfront}} = \frac{1}{8}\rho g H^2 \cdot \frac{gT}{4\pi} \qquad (4.13)$$

where T is the wave period, H is wave height (crest-to-trough), and ρ is the seawater density. They also report that substitution of the significant wave height and a characteristic period into the equation produces an overestimate of power by a factor of two. Compensation for this error by use of a too-low characteristic period is common. The factor $gT/4\pi$ is the wave group velocity, and can be expressed as $L/2T$, where L is the wave length. Use of average period and wavelength in computing wave power also provides compensation for the overestimate described above. Hoffman et al (81) use an expression for wave power derived by Baird (99) which provides this compensation,

$$\frac{\text{Power}}{\text{ft wavefront}} = \frac{\rho H^2}{8} \cdot \frac{L}{2T} \cdot \frac{g}{g_c}$$

$$= \frac{\rho H^2 g}{8 g_c} \cdot \frac{L}{2T} \tag{4.14}$$

One hundred square miles of farm is equivalent to a square ten miles or 52800 feet on a side. With ten miles of wave front and 64,000 acres per farm, the incident wave energy can be expressed as:

$$\text{hp/farm} = \frac{52800 \ H^2 L}{137.5 \ T} \tag{4.15a}$$

and

$$\text{hp/acre} = \frac{52800}{64000} \frac{H^2 L}{137.5 \ T} \tag{4.15b}$$

In addition, if a linear array of wave power collecting devices were aligned perpendicular to the dominant wave direction, its effective length (or the effective length of wavefront) would be less for those waves not travelling perpendicular to the array (98).

Isaacs, Wick, and Schmitt (100) overcome these difficulties by computing wave power from a weighted average of contributions from waves of all sizes and periods. Pierson and Salfi (98) have developed a computer routine to determine wave power for various west coast of the United States locations, using a weighted average of power contributed by the spectrum of wave heights and periods found at a specific location. Results of these claculations for monthly average wave heights and power for the year 1974 appear in Appendix D.

Table 4.9 presents upwelling water power requirements for growth rates of 1 to 50 tons/acre•yr and nutrient utilization efficiencies of 30% and 60%. Detailed calculations are presented in Appendix D. The column labelled hp in Table 4.9 shows the power requirements in horsepowers per acre for upwelling the quantity of water indicated in column 4. Column 5 presents

Table 4.9

UPWELLING AND DISTRIBUTION POWER REQUIREMENTS

Tons/acre/yr	Uptake Eff.	gpm/acre	hp/acre	hp/acre @ 25% eff.	hp/farm @ 25% eff.	Required hp/ft
1	60%	42	.05	.21	1.3×10^4	.26
	30%	83	.10	.41	2.6×10^4	.5
5	60%	208	.26	1.0	6.4×10^4	1.2
	30%	416	.52	2.1	1.3×10^5	2.6
10	60%	420	.52	2.1	1.3×10^5	2.6
	30%	840	1.1	4.2	2.7×10^5	5.1
30	60%	1250	1.6	6.2	4.0×10^5	7.5
	30%	2500	3.1	12.5	8.0×10^5	15.2
50	60%	2090	2.6	10.4	6.7×10^5	12.6
	30%	4190	5.2	20.8	1.3×10^6	25.2

the power input requirement assuming 25% conversion of input power to upwelling power. Column 6 lists the total farm upwelling horsepower (= column 5 x 64,000 acres), and column 7 the required incident wave power (in hp/ft) for a farm 10 miles on a side (= column 7 ÷ 52800 ft).

Table 4.9 indicates the incident wave power requirement for 30 tons/acre/yr DAF algal growth at 60% nutrient uptake and 25% input to pumping power efficiency as 7.5 hp/ft. Examination of Tables D.10, D.11, and D.12 reveals that average monthly incident wave power falls significantly below this level for July and August in every case. Information for September and October are not available, but reported data show a marked decrease in incident wave energy during the summer months, which may continue into the autumn.

The tables show only a part of the extreme seasonal and positional variability and give no indication of the very large daily and weekly variations in wave power (98).

The summer months have the greatest seasonal solar insolation, therefore the greatest algal growth rates would be expected during these months. The radiation imbalance which drives atmospheric circulation is virtually eliminated, winds over the ocean weaken, and longitudinal effects virtually vanish during July and August (98). These months are therefore the times of least wave power, on average considerably less than the continuous power input required to provide the minimum nutrient for a 30 ton per acre per year algal growth rate.

Points of observation for Tables D.10, D.11, and D.12 are located within regions considered by Seligman (80) as possible open-ocean algae-farm sites, 1-9, 11, and 12 respectively.

Algal growth rate during the summer months may be greater than the annual average, and nutrient requirement correspondingly greater. Wave power does not appear sufficient to meet requirements for nutrient-rich water upwelling during the summer months, whether algal growth rate increases or not.

Hoffman _et al_ (81) present a table which gives the power (in hp/ft) for sea states 1 - 6, along with the significant wave height, average wave length, and average period for the various sea states. Table D.13 presents sea state and available power data, expressed as horsepower per foot of wavefront, horsepower per farm (and equivalent BTU value), and horsepower per acre for a 100 square mile farm. Appendix D details calculations.

Available wave energy may be increased by utilizing wave energy outside the farm boundaries, or by increasing the incident wavefront length. A 100 square mile farm design with 100 mile length and 1 mile depth would increase the wavefront by an order of magnitude (100 miles vs 10 miles). This is one design alternative. However, current, nutrient dilution by wave action, drag, and other effects are also magnified.

Wave energy is a site-specific consideration, as wind and waves may vary with location. For example, a farm with 30% nutrient utilization and 25% wave energy conversion efficiency would require an input of 4.2 hp/acre for an algal yield of 10 T/a•yr. Sea state 3 would provide only 4.0 hp/acre. Therefore a site with an average significant wave height of 6 feet would not provide sufficient energy for upwelling the required nutrients.

Even more critical is the power requirement for a yield of 30 T/A•yr, which is approximately 6 hp/acre (assuming 60% nutrient utilization). This is significantly greater than the wave energy available for a sea state 3 and leads to the conclusion that for high yields, it will be necessary to upwell water using fuel or electric driven pumps rather than wave energy.

4.6 Water Provision to Land-Based Systems

A detailed discussion of water sources which might supply land-based systems, e.g., specific streams and rivers at specific sites, is beyond the scope of this discussion. However it is worthwhile to discuss some aspects of water provision, point out some unknowns, and some economic factors.

An excellent summary is presented by Benemann et al in Ref. (101) of net evaporative losses for the 48 contiguous states. These may range from zero (an example is in southwestern Florida, where rainfall will exceed gross evaporation) to over 50 inches/yr in the desert southwest. The values have been established by measuring evaporation rates from small open pans, and subtracting from these values the net annual rainfall. There is reason to expect that these net evaporations might be higher than would be experienced with large land-based biomass growth systems. This is because mass transfer coefficients from small pans would be expected to be larger than from large bodies of the size (10 mi x 10 mi) contemplated, as follows from applicable mass transfer theory for flat plates. Lower net evaporation losses from larger water bodies may also be understood intuitively from the fact that as an unsaturated mass of air moves over a large body of water, fractional saturation will increase, and the driving force for transfer and thus transfer will be reduced. Some further quantification is obviously needed in this area, since lower net evaporation would reduce water needs and improve prospects for viability of land-based systems.

Leaching losses are an interesting case as well. Highest leaching losses (which will vary by orders of magnitude depending on soil type and the nature of underlying strata) are experienced with small bodies of water, whose dimensions are small in relation to the depth of underlying permeable strata. However the characteristic area envisioned for a single land-based system will be typically far larger than the available area through which water can leach. A simple application of resistance theory, or Darcy's law, suggests intuitively that at a given head, leaching losses would be less for a larger body than for a small one. Leaching losses should be minimal for a large land-based system, but more quantification is obviously needed.

As the basis for estimating system water requirements and estimating some economics it will be assumed that evaporative losses are 20"/yr and leach losses 10"/yr. With these assumptions the water requirement will be 1.9×10^7 ft^3/day or 221 ft^3/sec.

Some rough estimates of economics for two methods of water provision indicate that transport of water at this rate will not present a prohibitive cost. If the source of water is 20 miles from the farm and pumping work is not to exceed 1% of G.E.O., then a pipe slightly over 5 feet in diameter would be required, at a cost of 5 to 10 million dollars. Pressure drop would be 24 psi, and no energy at all would be required if the water source were over 50 feet above the farm. The cost of impounding a river is estimated at less than the pipe.

As a final comment, relating to leach losses and nutrient recycle, it is worth noting that at a leach loss of 10"/yr and 1 mg/l of nitrogen, leach losses of nutrient nitrogen would be less than 5 lb/acre year. This is less than 1% of the nutrient uptake of the biomass, and significantly, is a loss which would not preclude the high fractional recycles postulated in 4.5.1.

4.7 Hydraulics

An important criterion for practicality of the land-based aquatic biomass growth system is that flow configurations and rates necessary to meet transport and mass transfer needs do not lead to excessive energy consumption. Constraints on transport include the necessity to circulate liquid from one end of the farm to the other (a 20 mile round trip) and that nutrient levels must be sufficient at all points. The circulation time for one 20 mile round trip will be 7.45 days at the 0.17 ft/sec flow rate assumed earlier for surface aeration computations. Note this velocity is compatible with the assumed nutrient supply; and also, with the velocities used for mass transfer computations.

One possible configuration, a modification of that suggested by Benemann et al (101) is a series of parallel channels 10 miles long going from one side of the farm to the other. Fluid flows out and returns in adjacent channels. If as postulated these channels are 200 feet wide, then 132 such channels will be required. The computed head loss (Appendix D) for this configuration and flow velocity is 0.37 ft H_2O. (The single 180° bend loss is insignificant, corresponding to $< 10^{-2}$ ft H_2O.) Pumping energy at a 30% thermal-to-mechanical conversion efficiency is computed at 0.63% of G.E.O. which is quite practical. A further safety factor is afforded by the fact that pumping energy will drop as the cube of the flow rate; a halving of the velocity would reduce pumping work to less than 0.1% of G.E.O.

Considerations of other possible systems where the water surface is level, e.g., a dike-enclosed 100 mi^2 shallow lake with flat bottom, or a deeper, dike-enclosed 100 mi^2 area of irregular topography, leads to the same conclusion that for all of these potential designs pumping energies will be minimal. Thus circulation (pumping) energy does not appear to impose any serious drain in the land-based system if these are level. A discussion of the possible effects of more irregular topography is presented below.

4.8 Effect of Uneven Terrain

The likelihood of finding a 100 mi^2 area which is perfectly flat is small. There is, in fact, the probability that much of the terrain available for a contiguous 100 mi^2 system will be sufficiently uneven that circulating water must be pumped through an effective head. It is of interest to look at the magnitude of this constraint; Table 4.10 shows the allowable circulation time for pumping work not to exceed 1% of G.E.O. for the design assumptions shown. One effect of this constraint will be that with addition of nutrient at a single point in the circulation loop (probably the least costly option for addition) nutrient concentrations at the addition point will have to be higher than the 1 mg/1 cited in Section 4.6. For the case of the 50 foot effective head, nitrogen levels with single-point addition would need to be $\sim$ 40 mg/1 (with slight excess for a safety factor). It is judged that this is not a serious constraint.

A detailed examination of all possible flow configurations is beyond the scope of this analysis. Clearly, there are design configurations intermediate between the single near-level surface discussed previously in Section 4.7 and the multiple level configurations in which an effective head

Table 4.10

Allowable Circulation Times [1] for Various Effective Water Heads in Land-Based Biomass Growth Systems

Effective Head, feet	Minimum Allowable Circulation Time, Days
5	40
20	160
50	400

Assumption: Water depth = 30"; no power recovery.

(1) Assuming that pumping work may conserve no more than 1% of G.E.O. at 30% conversion efficiency.

is implicit. One intermediate option would be channels which follow the contour of the land much as with contour plowing. Further investigation of possible designs is needed.

4.9 Use of Ocean Water to Supply Land-Based Systems

It is clear that in some areas of the U.S. where sunlight is ample, fresh water supplies will either be insufficient or too expensive. Ocean water can also be used to supply land-based system water needs. An energy requirement will be associated with pumping the water inland to the height of the system. If the constraint is set that pumping work does not exceed 1% of G.E.O., a simplified analysis may be carried out assuming 20"/yr net evaporation in conjunction with tolerable salinity increases (leach losses are ignored) to give the maximum height above sea level which ocean water may be pumped. (Frictional losses in pumping are not considered.) Table 4.11 indicates results; from this limited evaluation, it is clear that the option of using ocean water cannot be practical for land much above sea level. Higher net evaporations as might be encountered in the U.S. southwest would make this constraint more severe.

[Note that power recovery turbines to recover energy from the outgoing stream might lessen this constraint. However the outflowing stream will have a lower volume than the influx, and, additionally the turbines will be less than 100% efficient. It appears that only around half the input energy could be recovered. Low-head turbines have, in addition, relatively high installed costs per kilowatt of capacity.]

4.10 Concentration Effects

Given the current state of knowledge and information available a discussion of concentration effects must be largely qualitative.

Concentration effects will become important when evaporative losses from water within a land-based system lead to a salt concentration which adversely affects growth. Toxic effects are likely to be restricted to highly

Table 4.11

Estimate of Elevation Constraint on Land-Based Biomass Growth System Using Seawater to Meet Water Needs

Tolerable Salinity Increase, Per Cent	Makeup Water Required, ft^3/yr (1)	Maximum Allowable Elevation Above Sea Level (2)
10	4.65×10^{10}	8.3 ft
50	1.39×10^{10}	27.6 ft

(1) Assuming 20"/yr net evaporation.

(2) Assuming that pumping work cannot consume more than 1% of G.E.O.

soluble salts; water hardness per se is unlikely to cause a problem because solubility product relations will dictate precipitation of calcium and magnesium salts as their carbonates (under most circumstances) when input water is concentrated. The soluble salt level tolerable by the ultimate biomass of choice is obviously uncertain, and soluble salt components in water sources vary widely. Given all these uncertainties, the educated guess can still be made that a tenfold concentration of the salt component in water from most surface sources would be tolerable. The important consequence of this situation is that it will fix the system bleed at no more than 10% of the net evaporative loss. Thus system bleed requirements will add insignificantly (a few percent) to the water needs presented in Section 4.6.

4.11 Summary

The foregoing brief analysis of some factors relating to feasibility of biomass growth systems tends to the following conclusions.

1. For land-based systems, carbon dioxide transfer to any submerged biomass appears to present problems with sources and transfer methods examined. Energetics of sparging atmospheric air to provide CO_2 are unfavorable, and passive transfer gives inadequate rates. If power plant stack gas or another enriched source is used to provide CO_2, energetics are marginal with methods examined and there is a high associated capital cost. It is possible, however, that apparent CO_2 transfer problems could be overcome with some ingenuity.

2. The use of floating emersed plants for land-based system largely overcomes the CO_2 transfer problems described above. This is because of the high diffusivity of CO_2 in air relative to water, and the consequent lack of CO_2 diffused limitations for floating plants.

3. Nutrient recycle is highly desirable for land-based systems; with recycle, chemical fertilizer for make-up is a practical nutrient source in terms of energetics and dollar cost. With recycle, sewage may also be a practical nutrient source in some situations.

4. Nutrient mass transfer rates to roots of floating plants in land-based systems will be ample, with a large safety margin, over the range of nutrient concentrations and flow regimes which may be considered reasonable for a land-based system. This is also true of microalgae. It appears that nutrient leaching losses will likewise be minimal under most situations.

5. Hydraulics and pumping energies should be reasonable for any of several possible land-based design configurations, providing these configurations do not present the necessity for vertical water transport.

6. Any land-based system requiring vertical transport of water presents constraints because of the enormous amounts of water, and consequently pumping energy which will be needed. Thus there is a constraint on minimum circulation time for a land-based system if vertical water transport is required. If ocean water is used to supply needs of a land-based system, there is an effective limit on the height which water may be pumped above sea level to supply system needs. It appears that this limit is such as to preclude ocean water use for any except low-lying land.

7. Passive uptake of oxygen by a land-based biomass growth system may be sufficient to allow aerobic nutrient utilization by simple reintroduction of conversion process effluent into the system. If recycle by this method is possible, dollar and energetic costs should be very small.

8. As an over-all conclusion, it appears that there is a high probability that land-based aquatic biomass growth systems can be designed which are technically feasible, and for which growth energetics are quite favorable. (This does not necessarily imply economic feasibility.) This will be true providing aerobic nutrient recycle can be carried out.

9. The open ocean system design and analysis contains much uncertainty in the major design parameters of algae productivity, nutrient uptake, and water motion within the farm.

10. Water motion within the farm may be due only to displacement by upwelled water. Current and wave motion may be damped out in the farm interior, and surface water could become stagnant. If this condition occurs, nutrient-rich water may not be evenly distributed, and carbonates may be depleted in the surface water, thereby raising the pH and inhibiting growth.

11. The efficiency of nutrient uptake is dependent on uniform distribution of nutrients throughout the farm, which has not been experimentally demonstrated in the potentially

stagnant surface water of the farm interior for distribution pipes located 210' or 369' apart.

12. Wave power is insufficient for nutrient-rich water upwelling and distribution requirements for high yields. Approximately 30% of farm gross energy output (assuming 25% conversion from input energy to pumping energy, and 60% nutrient uptake) is required for upwelling nutrient-rich deep ocean water, independent of yield.

13. Mass transfer considerations indicate that nutrient transport to kelp may not be sufficient to maintain 5.7% per day growth rate if mixing by wave motion is small or residence time is less than predicted from hydraulic considerations.

14. Nutrient provision by upwelling deep ocean water is the only feasible technique (recycle and commercially available nutrient are infeasible in an open system).

15. Drag due to ocean current on the farm is estimated to be in the range of 29×10^6 to 55×10^6 lb_f for a 1 knot current.

16. The most favorable design assumptions indicate only a marginal net energy production, which, as is shown in Section 5, may be at an overly expensive cost.

Section 5

SYSTEM ANALYSIS

The design concepts and economic analyses for "base-line" ocean and land aquatic biomass systems are presented in this section. The economic analysis for each will consist of a range of expected costs, primarily due to many unanswered questions pertaining to assumptions used to develop the designs. A sensitivity analysis will be used to identify variables which could significantly change the unit cost.

5.1 Economic Analysis

The modeling of economics of a process consists of a determination of capital expenditures and operating costs, and a method to combine both to obtain the unit cost. The procedure used in this study for determination of unit gas cost is based on one developed by the American Gas Association (entitled "General Accounting Procedures to be Used for Large-Scale Production of Gas from Coal and Oil Shale," May 1, 1961), and modified by Panhandle Eastern Pipeline Company (1971). This procedure is described in a report from Esso Research and Engineering Co. (104) to the Federal Power Commission ("Descriptions of Gas Cost Calculation Methods" by H.M. Siegel, T. Kalina, and H.A. Marshall). Table 5.1 defines the procedures necessary for the unit cost calculation using a utility financing method.

The average unit cost can be determined from:

$$UC = \frac{N + 0.05\ (C - W) + 0.5\ [p + \frac{TAXRT}{1-TAXRT}\ (1 - d)r](C + W)}{Y \times A} \qquad (5.1)$$

Table 5.1

UNIT COST CALCULATION PROCEDURE

UTILITY FINANCING METHOD*

Basis:

- 20-year project life
- 5%/year straight line depreciation on Total Capital Requirement excluding Working Capital

Essential Input Parameters:

- Debt/equity ratio used to split Total Capital Requirement (75/25 assumed for analysis)
- Percent interest on debt (9%)
- Percent return on equity (15%)
- Federal income tax rate (48%)

Derived Parameters:

- Rate Base = Total Capital Requirement less Accrued Depreciation (includes 1/2 depreciation for given year)
- Percent Return on Rate Base = Fraction Debt x Percent Interest + Fraction Equity x Percent Return on Equity

Calculated Cash Flows in Given Year:

- Return on Rate Base = Rate Base x (Percent Return on Rate Base ÷ 100)
- Return on Equity = (Fraction Equity x Rate Base) x (Percent Return on Equity ÷ 100)
- Federal Income Tax = Return on Equity x (Percent Tax Rate ÷ [100 - Percent Tax Rate])
- Depreciation = 0.05 x (Total Capital Requirement - Working Capital)
- Total Revenue Requirement in Given Year = Return on Rate Base + Federal Income Tax + Depreciation** + Total Net Operating Cost

Unit Costs:

- In given year: Total Revenue Requirement ÷ Annual Production
- 20-year average: Total Revenue Requirement Over Project Life ÷ (20 x Annual Production)

Notes:

* AGA Method as modified by Panhandle-Eastern Pipeline Company and used by Synthetic Gas-Coal Task Force

** Depreciation is split according to the debt/equity ratio and used to pay back debt and equity in annual installments. (Working Capital is used to offset unpaid debt and equity at the end of the project life.)

where N = total net operating cost, \$/year

C = total capital requirement, \$

W = working capital, \$

p = fractional return on rate [$p = di + (1 - d)r$]

TAXRT = federal tax rate (fractional)

d = fraction debt

r = return on equity, fraction/year

i = interest on debt, fraction/year

Y = annual product, (T/Acre·Year)

A = area (Acres)

UC = unit cost (\$/T)

The first term on the right corresponds to the net operating cost; the second term is for 5% per year straight-line depreciation; the last term accounts for both return on rate base and federal income tax. The sum of these terms gives the total annual revenue requirement. The unit cost is obtained by dividing the average annual revenue requirement by annual production. Note that equation 5.1 gives the unit cost averaged over a twenty-year period.

The procedures for calculating the total capital requirement are outlined in Table 5.2 and the net operating cost procedure is given in Table 5.3.

It is essential to note that this study presents concepts for large-scale aquatic biomass systems and does not include specific detailed designs. Rather, designs are presented in detail sufficient to enable an estimate of capital and operating costs.

The analysis presented here does not include any credits for by-products which could result from the biomass-to-energy system. The value of any by-products can be used to reduce the costs of producing algal biomass.

Table 5.2

CALCULATION OF TOTAL CAPITAL REQUIREMENTS

Total Capital Investment (Installed)	XXXXX
Contractors Fee = 0.1 (Tot. Cap. Inv.)	XXXX
Engineering = 0.05 (Tot. Cap. Inv.)	XXX
Subtotal Plant Investment	XXXXX
Project Contingency = 0.15 (Sub. Pl. Inv.)	XXXX
Total Plant Investment	XXXXX
Interest During Construction at XX Percent (Tot. Pl. Inv.) (2 years)	XXXX
Start-Up = 0.2 (Tot. Gr. Oper. Cost)	XXXX
Working Capital = 0.02 (Tot. Pl. Inv.)	XXX
Total Capital Requirement	XXXXXX

Table 5.3

CALCULATION OF OPERATING COSTS

(90% Plant Service Factor)

Nutrient (at XX $/T)	XXX
Water Make-up (at XX $/MM Gal.)	XXX
Power (at XX $/KWH)	XXX
Fuel (at XX $/MM Btu)	XXX
Operating Labor	XXX
Maintenance Labor (= 0.015 * Tot. Pl. Inv.)	XXX
Supervision (0.15 * Oper. and Maint. Labor)	XXX
Administration and Overhead (60% of Total Labor including Supervision)	XXX
Operating Supplies (= 0.3 * Oper. Labor)	XXX
Maintenance Supplies (= 0.015 * Tot. Pl. Inv.)	XXX
Local Taxes and Insurance (= 0.027 * Tot. Pl. Inv.)	XXX
Total Gross Operating Cost (Per Year)	XXXXX

5.2 Open Ocean System

The design considered for the open ocean farm is a variation of the design developed by Integrated Sciences Corporation (78) for the Energy Research and Development Administration (now Department of Energy). The ISC design was a 100,000 Acre kelp farm with a yield of 340 T/Acre·Year wet harvest, containing 12.5% solids and 44% of the solids was ash. The farm substrate, to which kelp plants were attached, was located 100 feet below the surface and was positioned dynamically. Nutrients are provided by upwelling nutrient-rich deep ocean water. Harvesting was performed six times per year by ship. A support system provided living and work space for operating and maintaining the farm.

The system presented in this report differed from the ISC design by assuming (i) fixed (or moored) positioning; (ii) substrate depth of 60 feet; and (iii) yield of 13-666 T/A·Yr wet harvest with 7.5% of wet weight equal to dry ash free weight, i.e., 1-50 T daf/A·Yr.

The costs for the open ocean system are presented in Figure 5.1 (unit cost vs. yield), Figure 5.2 (equipment cost vs. yield), and Tables 5.4, 5.5, 5.8 and 5.9. These figures and tables present the costs as ranges for each yield. The intent of this approach is to indicate the variation in costs for the system using both optimistic design assumptions and design assumptions which reflect the probable conditions of operation. The specific assumptions used and their implications are discussed below for each subsystem of the farm.

The unit cost ($/Ton daf) presented in Figure 5.1 and Table 5.4 can be approximated (for the most optimistic assumptions) by the relationship

$$U = 960\ Y^{-0.65} \qquad (Y > 5) \tag{5.2}$$

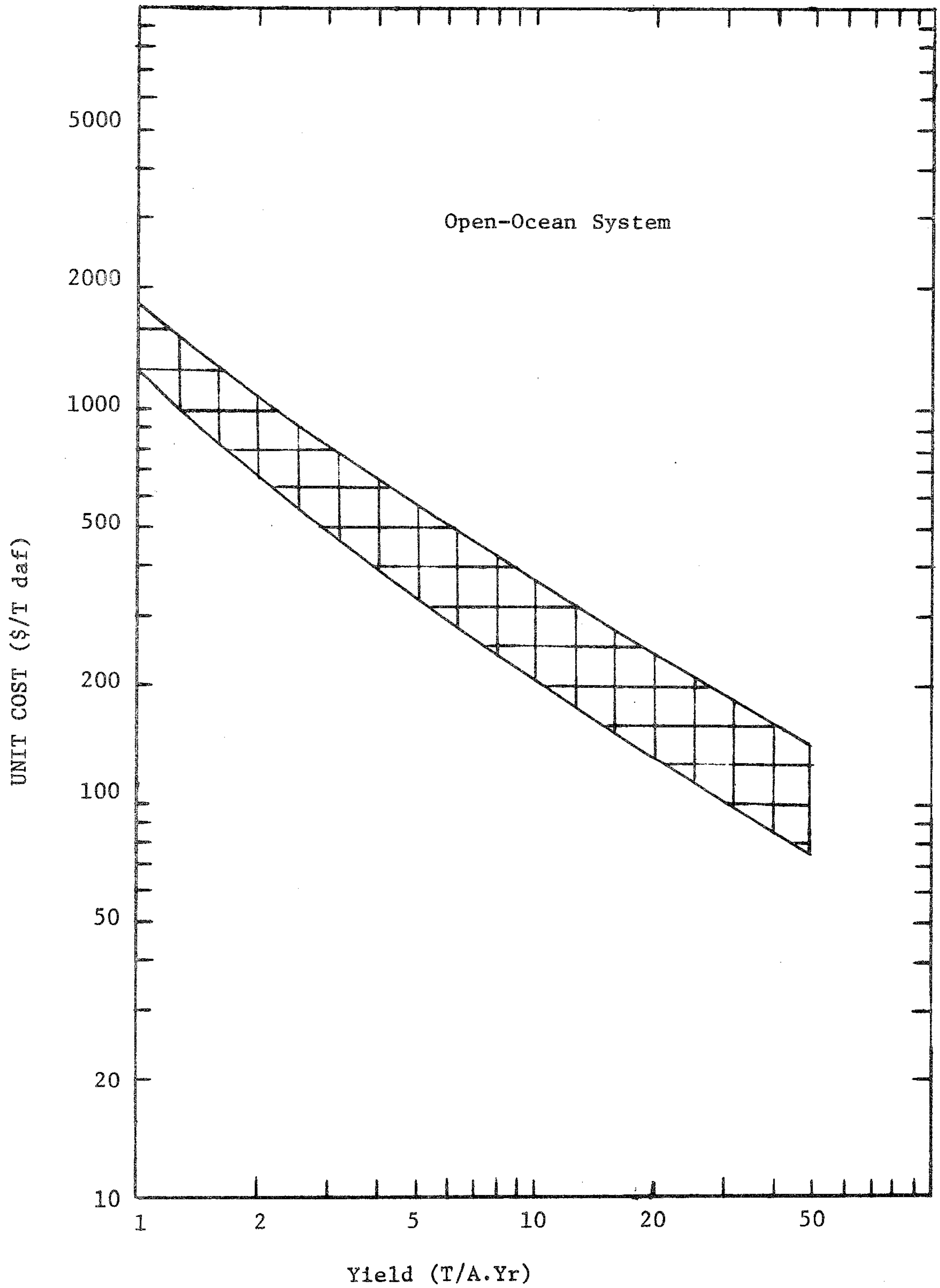


Figure 5.1

Range of Unit Costs

Table 5.4

UNIT COST

Yield T(daf)/A·Yr	Unit Cost \$/T(daf)
1	1233 - 1848
5	341 - 564
10	205 - 359
30	102 - 191
50	76.5 - 143

where Y is yield (T daf/A·Yr). For the maximum expected yield of 30 T daf/A·Yr*, the unit cost is \$102/T daf. It should be noted that this cost is for the situation using optimistic design assumptions. The unit cost would be significantly higher with lower yields or more realistic design assumptions. For the case using more realistic design assumptions (as indicated in Section 5) the unit cost can be approximated by

$$U = 1400\ Y^{-0.65} \tag{5.3}$$

and for the maximum expected yield of 30 T daf/A·Yr the cost is \$150/T daf, which is 50% greater than the cost using the most optimistic design assumptions.

5.2.1 Capital Costs

The range of equipment costs for each subsystem (substrate, nutrient supply, harvesting, positioning, and support) is presented in Figure 5.2 and in Table 5.5 with the percentage contribution for each subsystem. Since the major contribution to the cost is due to the nutrient supply system, more detail will be presented on this aspect of the farm and the assumptions which significantly affect costs. The other subsystems will also be analyzed to determine cost variability.

5.2.1.1 Substrate

The primary function of the substrate is to provide a site to which the kelp plant holdfast can attach. The substrate, consisting of a grid of lines and other structural members, must be designed to withstand the drag forces encountered due to currents, and the lines must be kept in tension to prevent entanglement and collapse of the structure.

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*At a meeting at the Department of Energy, February 16, 1978, several experts in the area of kelp research, namely, M. Neushul and D.A. Coon of University of California at Santa Barbara and W.J. North of California Institute of Technology, indicated the maximum expected productivity to be 30 T daf/A·Yr.

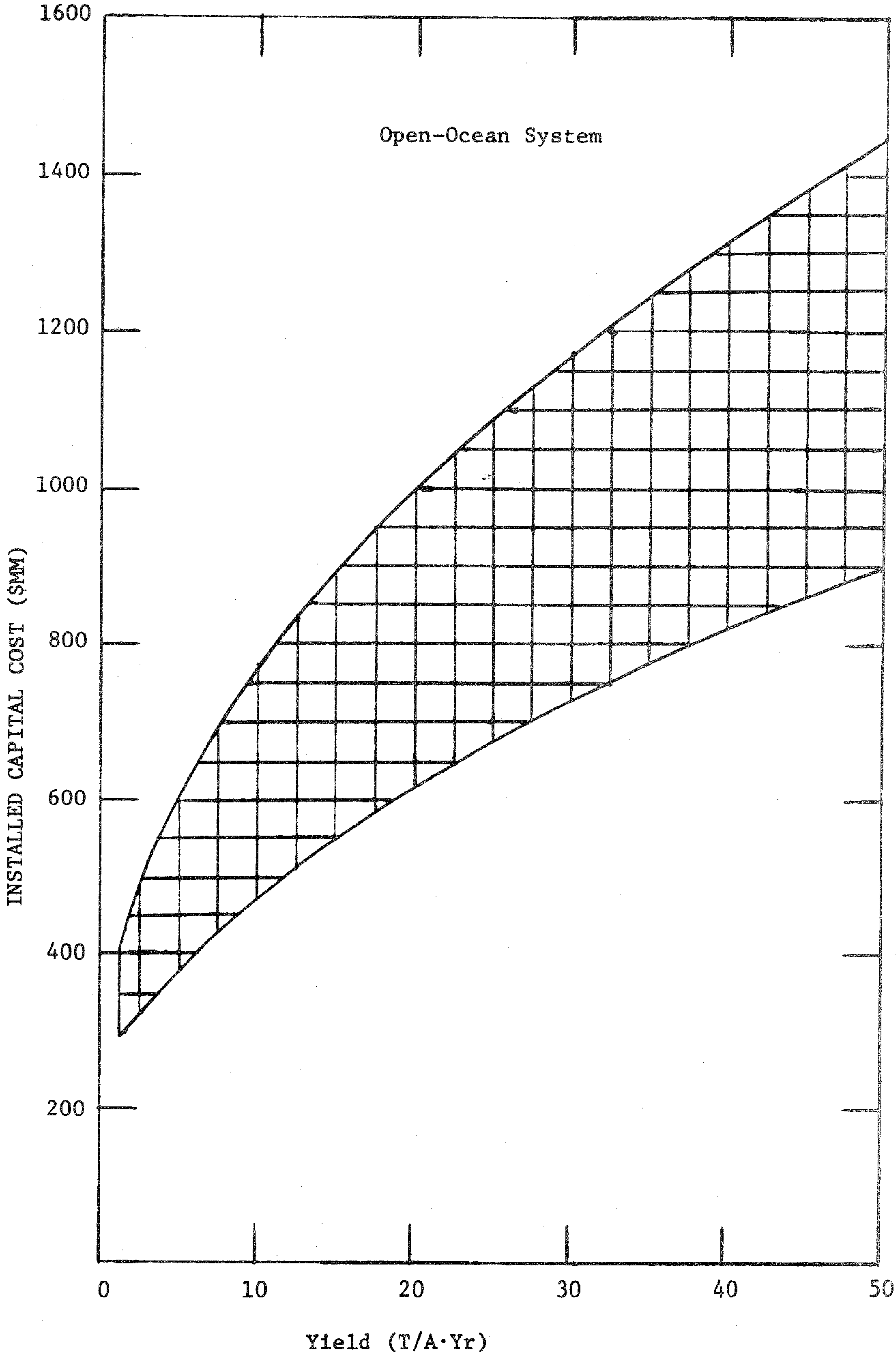


Figure 5.2

Installed Capital Costs

Table 5.5

CAPITAL COSTS(1)

	Yield (T/A·Yr)				
	1	5	10	30	50
Substrate	57 (29-20)	57 (21-13)	57 (17-10)	57 (12-7)	57 (9-5)
Nutrient Supply	101-144 (51-50)	167-253 (60-57)	213-343 (63-61)	341-577 (68-69)	434-731 (69-71)
Harvesting	8-56 (4-19)	22-105 (8-24)	35-130 (10-23)	72-179 (14-21)	110-214 (17-21)
Mooring	20 (10-7)	20 (7-4)	20 (6-4)	20 (4-2)	20 (3-2)
Support	11 (6-4)	11 (4-2)	11 (3-2)	11 (2-1)	11 (2-1)
Installation(2)	95-116	128-171	151-216	215-333	261-410
Total	292-404	405-617	487-777	716-1177	893-1443

(1) Cost expressed in \$MM, numbers in (   ) are % of total uninstalled cost.

(2) Installation cost is assumed to be 50% of capital cost, excluding harvesting vessels.

The ISC design consisted of triangular shaped modules, one thousand feet on a side (approximately 10 acres), with each side consisting of flexible tensioning lines held in tension by propulsors on buoys located at the module corners. However, the propulsor system, which also serves to dynamically position the farm, would require a complex control system and also consume over 5% of the energy produced, and therefore will not be considered as a design alternative for this study. Possible designs to maintain the structural shape of the substrate include use of rigid members or a mooring system based on tension-leg designs developed for the offshore drilling industry (105).

The sizing of the substrate will be dependent on the drag forces impinging on the farm. Section 4.3 presents the analysis of drag forces (similar to the ISC analysis) from which the substrate size can be determined. The ISC data were used to determine intermediate size line strengths and costs as presented in Figure 5.3 for braided nylon rope. The resulting cost for substrate tension lines is $\$21 \times 10^6$. The assumptions used to determine this cost are

(a) a 1 knot current;

(b) drag calculated (Appendix D) for a rough, solid flat plate, 10 miles on a side and 60 feet deep;

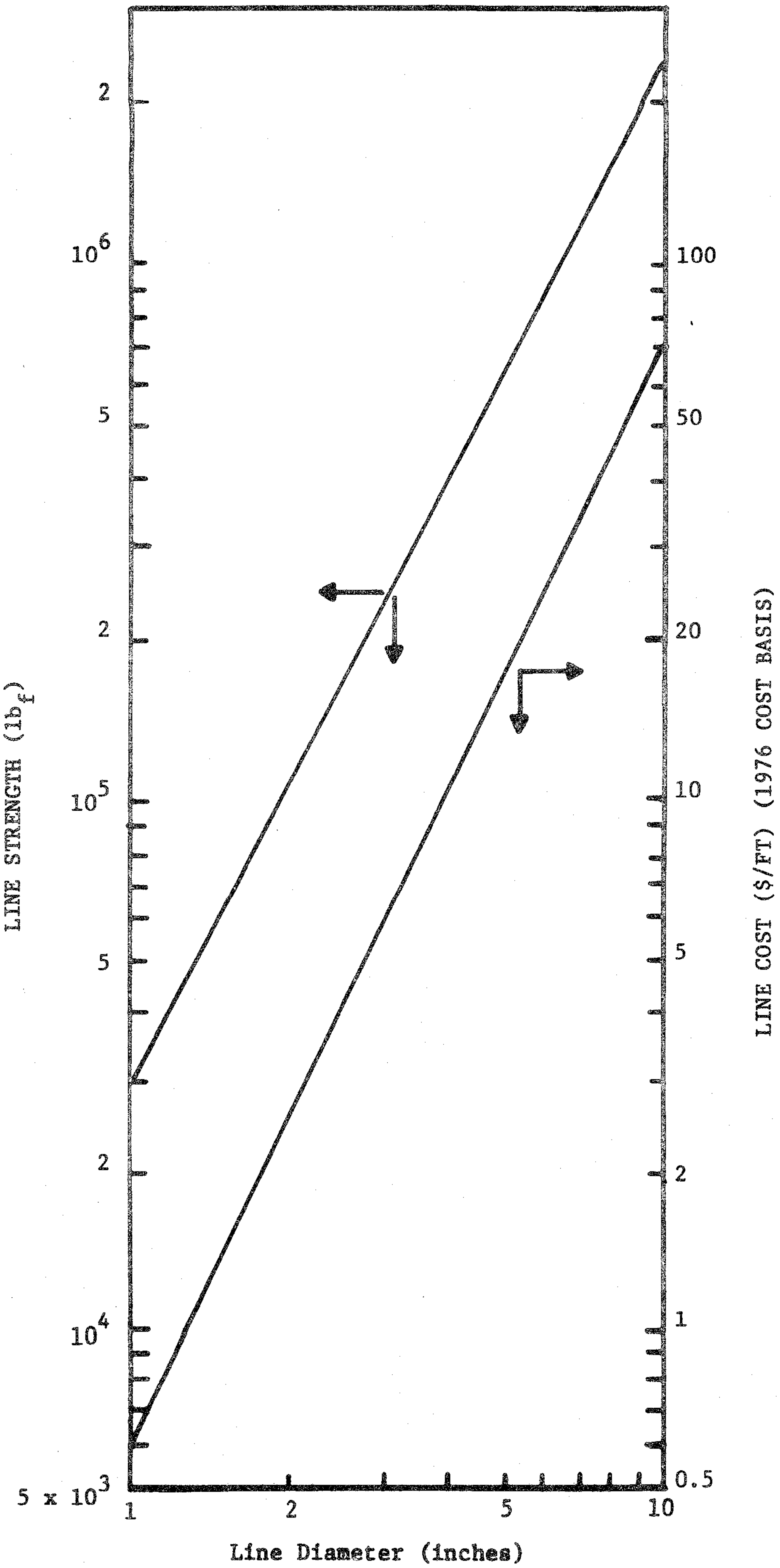
(c) a factor of safety of 10 for interior lines and 5 for the circumferential lines;

(d) line strength to line diameter relationship as presented in Figure 5.3.

It is essential to provide a means of maintaining the lines in tension. If rigid members are used, tension lines, as described above, will probably be unnecessary. However, the cost of such rigid members will

Figure 5.3

Estimates of Line Strength and Cost



be greater than line costs, so the $21 million is the more economical approach to a substrate which must be maintained in tension.

If a mooring approach is combined with the substrate to maintain tension, buoys located at the module corners will be necessary. The cost of these buoys is $14 million. The assumptions used for this cost are

(a) drag calculations as presented above;

(b) design safety factor of five;

(c) design and cost of buoys determined by the ISC approach, but updated to 1977 costs.

The substrate also contains a grid network which functions as the bottom to which the holdfasts are attached. Depth buoys will be used on the grid network to assist in maintaining the substrate geometry. The costs of these components were taken from the ISC report, but modified because of farm size and updated to present costs. The grid network cost is $6 million and the depth buoy cost is $16 million.

The cost of the substrate is thus $57 million. This cost is dependent on the analysis of system drag. Higher drag forces would result in higher line tensions and therefore higher system cost.

5.2.1.2 Nutrient Provision

Nutrients will be provided by upwelling nutrient-rich ocean water from depths of 500-1500 feet. The upwelling system consists of upwelling pipes, pumps to provide power for upwelling, and a pipe system to distribute nutrients throughout the farm. The sizing of the upwelling system will be dependent on flow rate of upwelled water, which is dependent on yield, nitrogen content in kelp (assuming nitrogen is the limiting nutrient), nitrogen content in upwelled water, and nutrient utilization. The established set of design assumptions include:

* Plant Nitrogen content = 1.6% of daf weight
* Nutrient required for farm maintenance = Nutrient required for harvested weight x 0.20
* Nutrient uptake efficiency = 30-60%
* Water nitrogen concentration = 25 μg-AN/ℓ at 500 feet of depth
* Upwelling and distribution head amounts to 4.8 ft. of water.

Some of these design assumptions are site-specific. For example, upwelling from a depth of 1500 feet of water may be required to obtain 25 μg-AN/ℓ concentrations.

5.2.1.2.1 Water Requirement

The water flow rate and power requirements for these assumptions are presented in Table 5.6. The variations are due to the nutrient uptake efficiency assumption of 30-60%. The analysis of the uptake efficiency assumptions is presented in Section 5.2.1.2.4.

The values in Table 5.6 are based on 25 μg A N/ℓ nutrient concentration in upwelled water. Any change in this concentration will inversely affect the upwelling requirements. Literature sources present conflicting data. Seligman (80) indicates 25 μg AN/ℓ at 500 ft., while Sverdrup (71) indicates 10 μg AN/ℓ at 500 ft., but 30 μg AN/ℓ at 1500 ft.

It is assumed that the kelp nitrogen content is 1.6% daf, which exists when the plant is provided with limited nitrogen and results in a state of low nitrogen storage in the plant. At this nitrogen concentration, the plant appears healthy and will grow (106). Higher plant nitrogen

Table 5.6

UPWELLING REQUIREMENTS*

Yield T daf/A·Yr	30% Nutrient Utilization Flow Rate GPM/Acre	Power hp/Acre	60% Nutrient Utilization Flow Rate GPM/Acre	Power hp/Acre
1	83	0.10	42	0.05
5	417	0.52	209	0.26
10	835	1.04	417	0.52
30	2504	3.11	1252	1.56
50	4173	5.18	2087	2.59

*25 μg A N/ℓ concentration in water
1.6% N in kelp (daf basis)

content would occur if the limiting condition cannot be attained and the plant absorbs and stores excess nitrogen. This would then result in greater upwelling requirements. For example, a 2% nitrogen content rather than 1.6% results in a 25% increase in upwelling flow rate.

5.2.1.2.2 Pipe Design

The flow rates indicated in Table 5.6 can be combined with assumed design friction losses due to flow to determine pipe diameters for the upwelling and distribution system, using the relationship (Appendix C)

$$\frac{\Delta P}{L} = \frac{32Q^2\rho}{\pi^2 D^5} \cdot f \qquad (5.4)$$

The design friction losses assumed for this analysis are

(i) 1 ft. head loss due to friction in the upwelling pipe;

(ii) 3 ft. head loss due to friction in distribution system;

(iii) the friction loss in the distribution system is equally distributed between the distribution pipes and the pipes feeding water from the upwelling pipe to the distribution pipes.

The pipe diameters calculated by this procedure are presented in Table 5.7 for the assumption of one upwelling pipe supplying 50 Acres, with assumed distribution systems as presented in Figure 5.4, i.e., distribution pipes spaced either 210 ft. or 369 ft. There are several additional design assumptions used to obtain these pipe diameters, as follows:

(i) There are additional friction losses in the upwelling pipe attributed to bending of the flow path. This occurs when the flexible plastic pipe bends as a result of current flow and there is a 90° bend at the point of entering the feeder pipe. It was assumed that half of the total friction loss in the upwelling pipe was due to these effects.

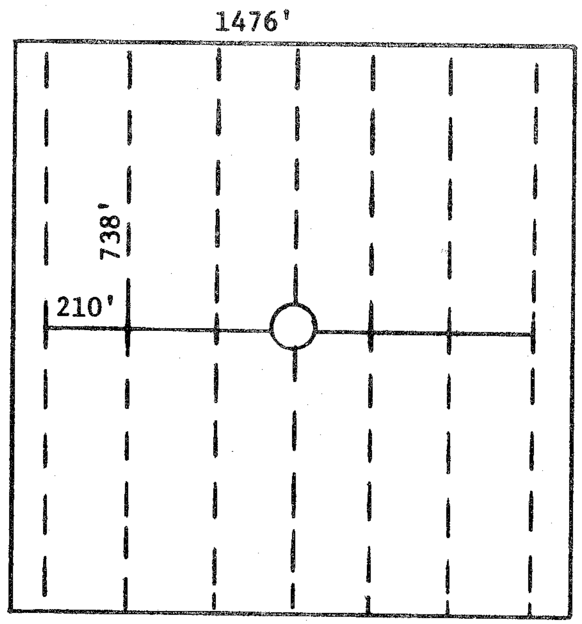
Table 5.7

PIPE DESIGN*

	Pipe Diameter (Feet)	
	10 T/A·Yr	30 T/A·Yr
Upwelling	3.7	5.7
Distribution (369' apart)	1.5	2.3
Feeder	2.6	4.0
Distribution (210' apart)	1.2	1.8
Feeder	2.3	3.6

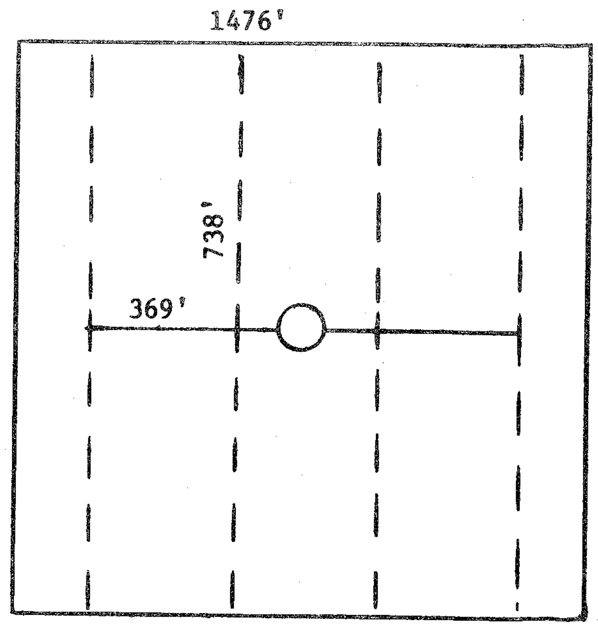
*1 upwelling pipe per 50 acres

60% nutrient utilization (multiply diameters by 1.32 to obtain pipe size for 30% nutrient utilization)



Upwelling Pipe	6.4×10^5 ft/farm
Distribution Pipe	13.2×10^6 ft/farm
Feeder Pipe	1.6×10^6 ft/farm

(a) Distribution Pipes Spaced 210 ft.



Upwelling Pipe	6.4×10^5 ft/farm
Distribution Pipe	7.6×10^6 ft/farm
Feeder Pipe	1.4×10^6 ft/farm

(b) Distribution Pipes Spaced 369 ft.

Figure 5.4

Nutrient Distribution Systems (One Upwelling Pipe Per 50 Acres)

(ii) The distribution pipes were designed using the analysis presented in Appendix C, i.e., the friction loss used for calculation of diameter was taken to be three times the assumed friction loss.

(iii) No additional loss was attributed to bending in the distribution system. A more detailed analysis would require an estimate of these effects to determine the effect on pipe design.

(iv) It is assumed that the nutrient requirement is constant throughout the year. However, in reality, growth rate varies seasonally, and therefore, so will upwelling requirements. A more detailed analysis would incorporate these variations to provide the most economically and energy efficient pipe design to meet the variable requirements.

Costs of the nutrient supply system are presented in Table 5.5 and includes upwelling pipes, distribution and feeder pipes, pumps for upwelling, and buoys. The pipes were assumed to be made from polyethylene, with pipe costs indicated in Figure 5.5 (assuming $0.85/lb for pipe). Pump costs are approximated by (93)

$$\text{Cost} = 14.5\ Q^{0.75} \tag{5.5}$$

where Q is the flow rate (gpm).

Thus, depending upon the design assumptions, the capital cost for the upwelling system ranges from $341 million to $520 million for a yield of 30 T/A·Yr.

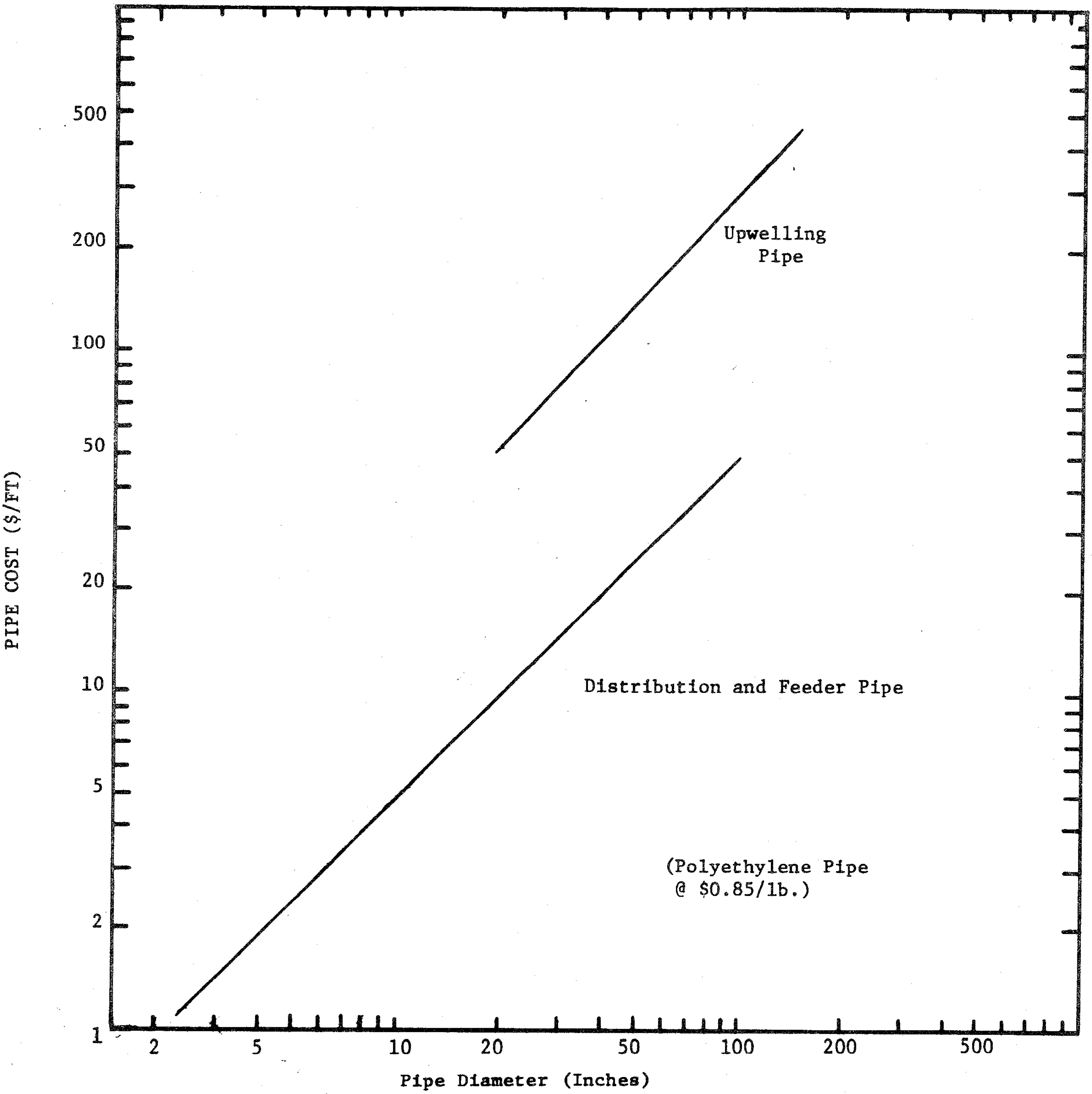


Figure 5.5

Estimated Pipe Cost

5.2.1.2.3 Upwelling Energy Requirements

The energy requirements for upwelling can be obtained from Table 5.6, assuming a 25% efficiency for pumping. This is a reasonable assumption for fuel or electric drive pumps. These are approximately 30% efficient converting fuel to mechanical energy. Axial flow pumps are approximately 80% efficient (97), giving an over-all efficiency of about 24%. The amount of energy required is proportional to yield, as is the total energy content of the harvested plant. Thus, for 60% nutrient utilization and 25% pumping efficiency, the energy required for upwelling is 30% of the gross energy content of the plant (assuming a content of 8,000 BTU per pound). For 30% nutrient utilization, 60% of the gross energy content is required for upwelling. In either case, it would be poor practice to design an energy production process in which such a high energy cost is attributed to only one aspect of the system. (An over-all energy balance is presented in Section 5.2.4 for the entire system, including the energy requirement associated with materials of construction.)

Since the upwelling energy requirement is such a high percentage of the gross energy content of the harvested plant, and since this percentage is extremely sensitive to process variables such as friction head losses and nutrient utilization efficiency, an approach to eliminate the use of fuel-powered pumps is desirable. One such approach is the utilization of environmental wave energy by wave pumps. This would eliminate the upwelling energy requirement from the operating expenses of the farm. However, the analysis of wave energy utilization presented in Section 4.5.3.3 indicates that there is not sufficient wave energy during the summer months (which also corresponds to the highest growth rates) to provide upwelled water to maintain yields of 30 T/A·Yr.

5.2.1.2.4 Nutrient Utilization

The efficiency of utilization of nutrients is an important aspect in the design of the nutrient supply system, as is indicated in Sections 5.2.1.2.2 and 5.2.1.2.3. A range of from 30 to 60% utilization was assumed and it is important to determine which end of this range is more reasonable. This would then allow a better estimate of an expected cost, not necessarily the lowest cost based on the most favorable assumptions.

Nutrient utilization is dependent on the coefficient of mass transfer of nutrients to the plant, residence time of nutrients in the farm, and surface area of plant. The maximum nutrient utilization, arising with plug flow is given by:

$$\text{nutrient utilization} = 1 - e^{-kA\tau} \qquad (5.6)$$

The mass transfer coefficient, k, increases with increasing flow velocity over the plant, and thus increases with mixing due to wave action and currents. The plant surface area, A, is a function of crop density and increases daily as the plant grows. The residence time, τ, is limited to a maximum which is the hydraulic retention time, defined as farm volume/flow rate. The actual retention time will be less than maximum due to dilution effects caused by currents and wave action and also to sinking of the higher density upwelled water. An analysis of these effects, presented in Section 4.2, indicates that 60% utilization will be attained under the most optimistic design assumptions.

5.2.1.3 Harvesting

Harvesting will be performed via vessels similar to those described in the ISC design. The vessel size, power requirements, and crew cost were determined using the relationships presented in the ISC report. The vessel costs are presented in Figure 5.6 for a farm located 100 miles from shore and ranging from 2 to 14 harvests per year. The effect of distance from shore on vessel cost is presented in Figure 5.7 for the case of 6 harvests per year.

An analysis of the harvesting scheme, presented in Appendix E, indicates that for a growth rate of 3% per day, about 7.5 harvests per year is required. This is a reasonable expectation of growth, resulting in a vessel cost which is approximately the mean of the values presented in Figure 5.6. The lowest harvesting costs, for 2 harvests per year, corresponds to a daily growth rate of about 0.8% which is extremely low for the amount of nutrient supplied and solar insolation expected. Higher daily growth rates require more vessels with corresponding increases in capital and operating costs. Also, higher growth rates do not guarantee higher productivity, since productivity is the product of standing crop and growth rate.

It is assumed that the farm location will be an average 100 miles from shore. Costs for deviations from this average location can be obtained from Figure 5.7.

5.2.1.4 Positioning

The base-line design assumes the farm will be moored at a 2500 ft. depth. The size and number of lines will be dependent on the drag forces involved. It is intended to have a mooring line at the corners of the triangular shaped modules discussed in Section 5.2.1. Thus 3200 mooring lines will be necessary. For the drag forces indicated in Section 4.3 for a 1 knot current and a safety factor of ten, 2-inch lines would be necessary. The cost of mooring line, using Figure 5.3, would be $20 million. The effect of increasing mooring depth or farm drag is to increase mooring costs. In fact, in the Pacific Ocean where the depth is greater than 10,000 ft. for most locations 40 miles off the U.S. west coast, the cost of mooring lines would be significantly greater.

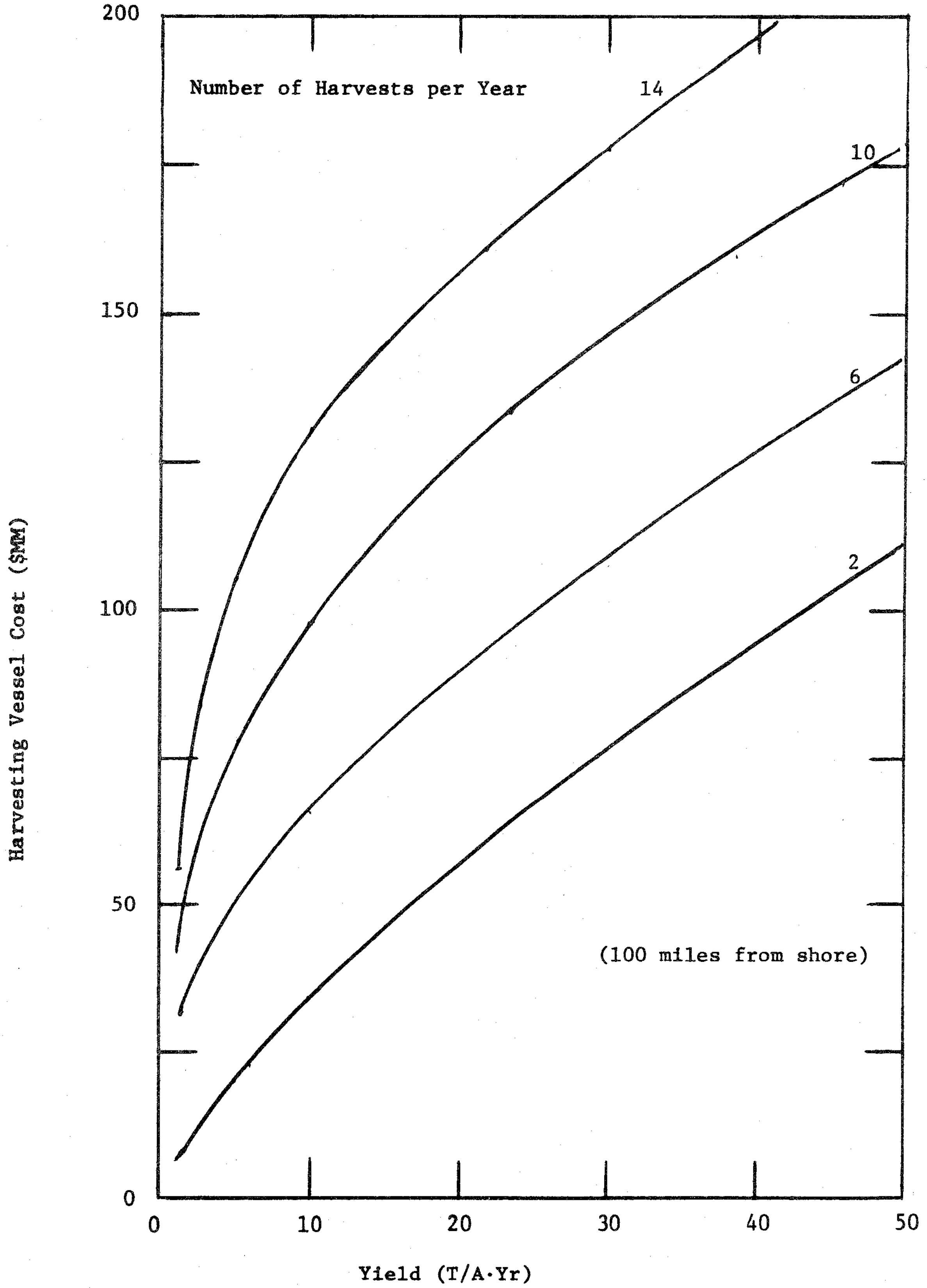


Figure 5.6

Harvest Costs as a Function of Harvesting Frequency

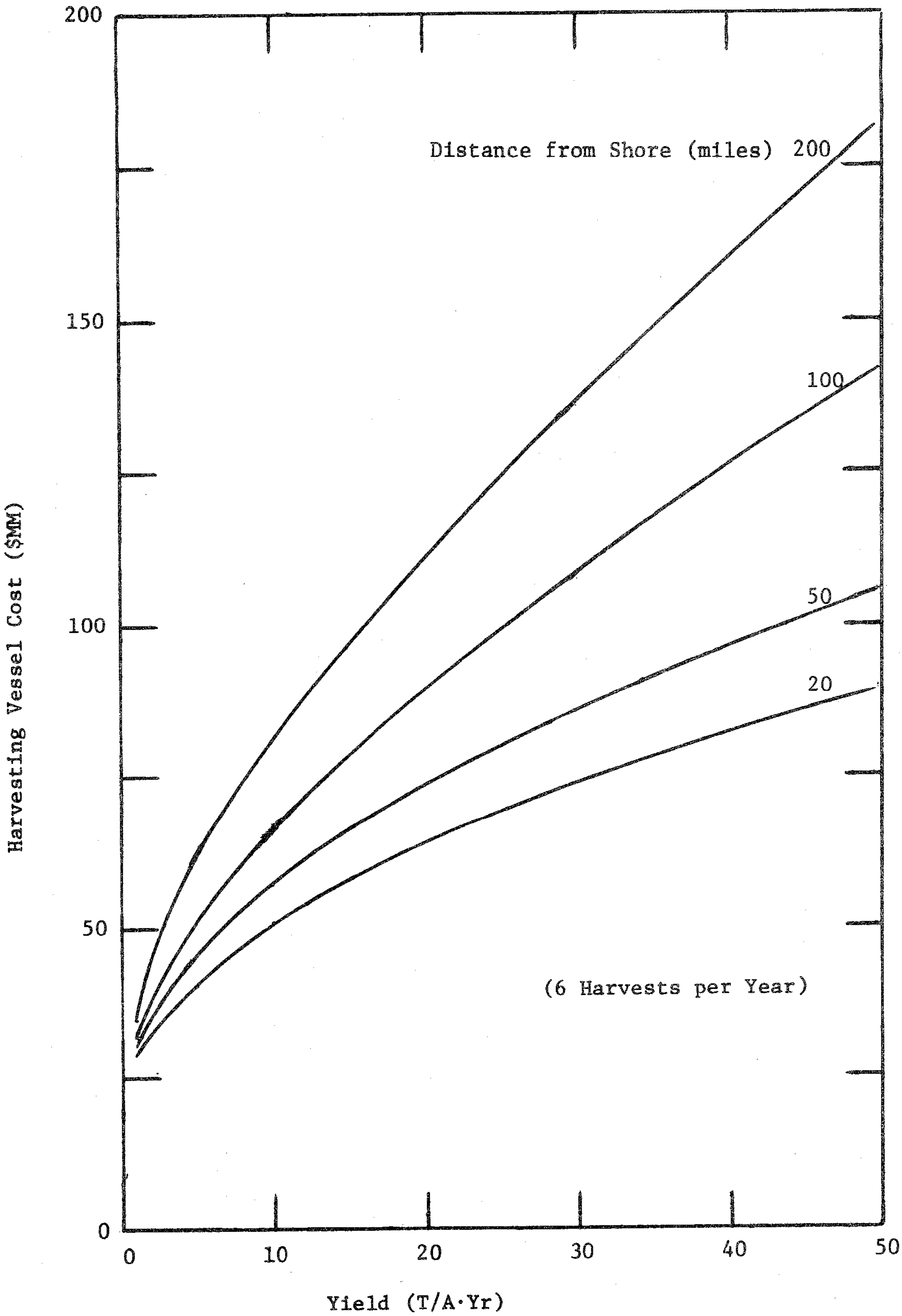


Figure 5.7

Harvest Costs as a Function
of Distance from Shore

5.2.1.5 Support

This aspect of the farm, a floating platform, will be similar to the ISC approach but will be smaller due to the smaller farm size and labor force. The cost of this platform was determined to be $11 million, based on the ISC design, and it will provide farm supporting services and living space for those working on the farm.

5.2.2 Operating Costs

Operating costs are presented in Table 5.8, with a range of costs representing variations in the design assumptions. Maintenance and insurance are directly related to the capital costs, as is indicated in Section 5.1 and Table 5.3. Operating labor consists of labor necessary for farm operation plus crew for the harvesting vessels. This latter item (approximated from the ISC report) is obviously dependent on the size and number of vessels, as is the fuel cost for operating the vessels. The fuel requirements for upwelling are dependent on nutrient utilization efficiency, pumping efficiency, and obviously whether environmental energy is utilized (hence the zeros indicated in Table 5.8 as the minimum for this item).

5.2.3 Total Capital Requirement

The range of total capital requirement is presented in Table 5.9 for the various assumptions discussed previously.

5.2.4 Energy Balance

The energy balance for any system consists of the following items:

(i) operating energy;

(ii) energy contribution due to materials of construction amortized over the life of the system;

(iii) gross energy production.

Table 5.8

OPERATING COSTS(1)

	Yield (T/A.Yr)				
	1	5	10	30	50
LABOR					
Operating Labor:					
Harvesting	1.2-6.8	1.6-6.9	1.7-7.2	3.6-9.0	5.4-10.8
Other	0.3	0.3	0.3	0.3	0.3
Maintenance Labor (1.5% Tot. Pl. Inv.)	5.8-8.0	8.0-12.3	9.7-15.4	14.2-23.4	17.7-28.6
Supervision (15% Oper. & Maint. Lab.)(2)	0.9-1.2	1.2-1.9	1.5-2.4	2.2-3.6	2.7-4.3
Overhead (60% Labor & Supervision)(2)	4.2-5.7	5.7-8.7	6.9-10.8	10.0-16.4	12.4-19.9
SUPPLIES					
Operating:					
Harvesting	0.1-0.3	0.1-0.3	0.1-0.3	0.2-0.4	0.2-0.5
Other	0.1	0.1	0.1	0.1	0.1
Maintenance (1.5% Tot. Pl. Inv.)	5.8-8.0	8.0-12.3	9.7-15.4	14.2-23.4	17.7-28.6
INSURANCE (1% Tot. Pl. Inv.)	3.9-5.3	5.4-8.2	6.4-10.3	9.5-15.6	11.8-19.1
FUEL - Harvesting ($2/MM Btu)	0.4-3.2	0.9-3.7	1.2-4.2	2.9-6.1	4.6-7.7
FUEL - Upwelling ($2/MM Btu)(3)	0-1.4	0-6.6	0-13.3	0-40.0	0-66.6
TOTAL	22.7-40.3	31.3-61.3	37.6-79.7	57.2-138.3	72.9-186.5

(1) Costs expressed as $MM per year.
(2) Excluding Harvesting Labor.
(3) Use of Wave Energy results in zero cost.

Table 5.9

TOTAL CAPITAL REQUIREMENT

Open Ocean System

	Yield (T/A·Yr)				
	1	5	10	30	50
Total Capital Investment (Installed)	292-404	405-617	487-777	716-1177	893-1443
Contractor Fee (10% Tot. Cap. Inv.)	29-40	41-62	49-78	72-118	89-144
Engineering (5% Totl. Cap. Inv.)	15-20	20-31	24-39	36-59	45-72
Subtotal Plant Investment	336-464	466-710	560-894	824-1354	1027-1659
Project Contingency (15% Sub. Pl. Inv.)	50-70	70-107	84-134	124-203	154-249
Total Plant Investment	386-534	536-817	644-1028	948-1557	1181-1908
Interest During Construction (9% x 2 yrs. x Tot. Pl. Inv.)	69-96	96-147	116-185	171-280	212-286
Working Capital (2% Tot. Pl. Inv.)	8-11	11-16	13-21	19-31	24-38
Start-Up (20% Oper. Cost)	5-8	6-12	8-16	11-28	15-37
Total Capital Requirement	468-649	649-992	781-1250	1149-1896	1432-2269

5.2.4.1 Operating Energy

There are two principal contributions to operating energy, namely, upwelling and harvesting vessels. The energy requirement for upwelling is presented in Table 5.6, and assuming a 25% conversion efficiency, the annual upwelling energy requirements are as indicated in Table 5.10. Obviously, the use of environmental wave energy will not affect this energy requirement, but it will eliminate the need for purchasing the energy or converting some of the product energy. Fuel requirements for harvesting vessels were determined using the relationships presented in the ISC report (78) and are also presented in Table 5.10.

5.2.4.2 Materials of Construction

Energy content of various materials has been reported in the literature (107, 108). The principal materials of construction for the open ocean system are indicated in Table 5.11 with the respective energy contents. The total energy content for the farm materials is presented in Table 5.11 and this energy content, amortized over the system life (assumed to be 20 years), is given in Table 5.10.

5.2.4.3 Gross Energy Production

The gross energy content of the harvested algae is assumed to be 8000 BTU/lb. (1.6×10^7 BTU/Ton) and the annual gross energy content is indicated in Table 5.10.

5.2.4.4 Net Energy Production

The percentage of gross energy utilized in the farm and net energy production (gross - utilized) are shown in Table 5.10. Yields below about 5 T/A·Yr result in a negative net energy production and are obviously unfeasible. Also, unit cost on a $/MM BTU basis should incorporate net energy production rather than gross energy production, and this is presented in Figure 5.8.

Table 5.10

ENERGY BALANCE[1]

Open Ocean System

	Yield (T/A.Yr)				
	1	5	10	30	50
Fuel - Upwelling	0.3-0.6	1.5-3.0	3.0-6.0	9.0-18.0	15.0-30.0
Fuel - Harvesting	0.2-1.6	0.4-1.9	0.6-2.1	1.5-3.1	2.3-3.9
Materials of Construction[2]	0.3-0.5	0.4-0.8	0.5-1.0	0.8-1.4	0.9-1.7
Total Energy Utilized	0.8-2.7	2.3-5.7	4.1-9.1	11.3-22.5	18.2-35.6
Gross Energy Production	1.0	5.0	10.0	30.0	50.0
Net Energy Production	$<$0-0.2	$<$0-2.7	0.9-5.9	7.5-18.7	14.4-31.8
% Utilized	80-270	46-114	41-91	38-75	36-71

(1) Energy expressed as 10^{12} Btu/Yr.

(2) Amortized over 20 years.

Table 5.11

ENERGY CONTRIBUTION FROM
MATERIALS OF CONSTRUCTION*
(10^{12} BTU)

	Yield (T/A.Yr)				
	1	5	10	30	50
Substrate	1.7	1.7	1.7	1.7	1.7
Nutrient Supply	2.6-5.4	5.2-10.6	6.8-14.1	10.9-22.3	13.4-27.8
Positioning	1.3	1.3	1.3	1.3	1.3
Harvesting	0.1-1.2	0.3-1.5	0.5-1.9	1.0-2.4	1.5-3.0
Support	0.1	0.1	0.1	0.1	0.1
Total	5.8-9.7	8.6-15.2	10.4-19.1	15.0-27.8	18.0-33.9

*Steel - 50 x 10^6 Btu/Ton
Nylon - 213 x 10^6 Btu/Ton
Polyethylene - 80 x 10^6 Btu/Ton
Concrete - 2.7 x 10^6 Btu/Ton

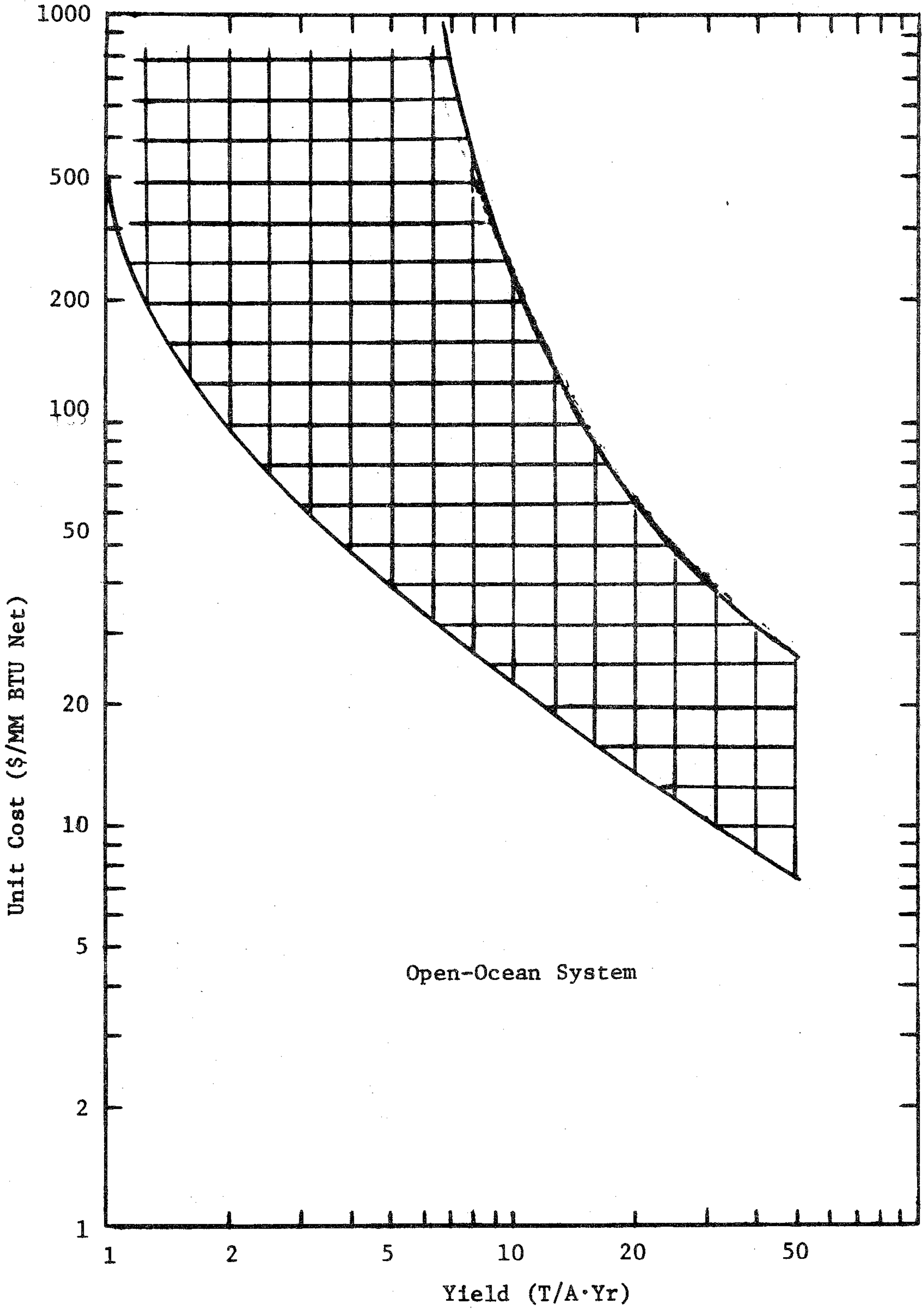


Figure 5.8

Cost Per Net Energy Production

5.2.5 Open-Ocean System Summary

The analysis for the open-ocean system utilized a range of design assumptions, the best being considered very optimistic. It is also important to indicate the results of the analysis for design assumptions which reasonably can be expected to be attained in actual practice. These reasonable design assumptions, based on analyses presented in this report, are:

(a) Nutrient utilization of 30%.

(b) Plant nitrogen content of 2% daf.

(c) Nitrogen content in upwelled water of 25 μg AN/ℓ.

(d) Upwelling system pressure loss of 4.8 ft. H_2O.

(e) Distribution pipes spaced 210 ft.

(f) One upwelling pipe per 50 acres.

(g) Fuel or electric driven upwelling pumps.

(h) Harvesting frequency of 6 times per year.

(i) Farm located 100 miles off shore.

The unit costs ($/Ton and $/MM BTU) using these design assumptions are presented in Figure 5.9, with the cost in $/MM BTU based on net energy production. Thus, for the maximum yield of 30 T/A·Yr., the algae cost would be approximately $170/Ton or $32/MM BTU. For a yield of 10 T/A·Yr., these costs will be significantly higher, $330/Ton or $80/MM BTU.

The design analysis was made for average conditions over the year. However, in actual practice these conditions can be expected to vary with time. For example, growth rate and yield will be greater during the summer months, thus requiring more nutrients per day and more frequent harvesting. It is essential that any design is capable of accomodating any expected significant deviations from the average conditions. This was not done for this analysis of conceptual designs but must be included in more detailed design analyses.

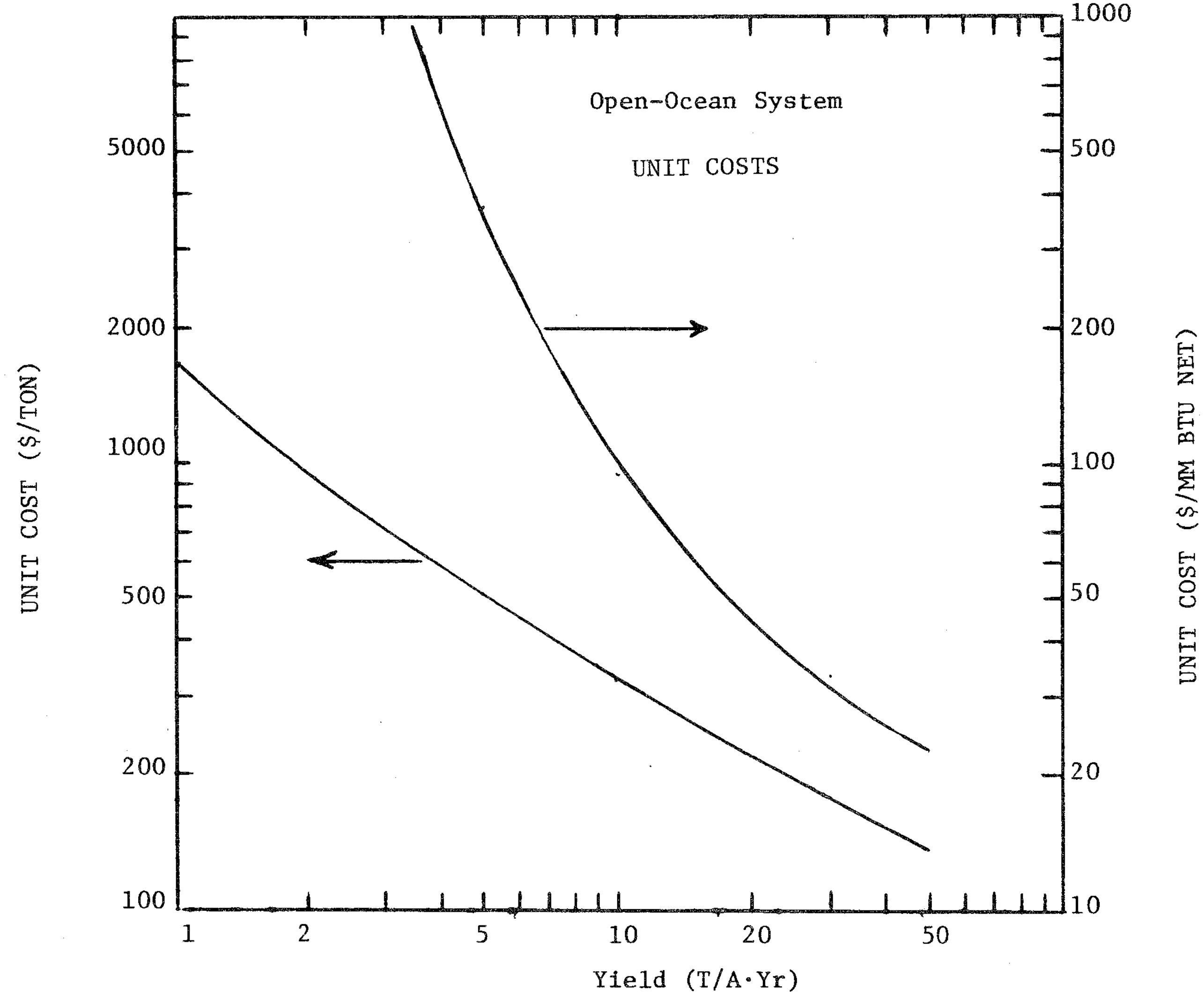


Figure 5.9

Unit Cost Based on
Most Probable Conditions

5.3 Land Based Systems

In order to evaluate the potential economics of 100 land-based aquatic biomass systems of 100 sq. miles each, a representative design was developed. No one of the potential 100 systems would be built exactly as described in this representative system. This is due to the varying site specific conditions and expected evolution of the art prior to construction. A block diagram for this representative system is presented in Figure 5.10. The system components between the dashed lines were considered in the analysis. This design of a large scale microalgae system, developed by CSO International, appears in Appendix B. It is expected that this design will be considered as a representative base from which modifications can be made.

The economics of the CSO design, with modifications discussed later, are presented in Figure 5.11 and Tables 5.12, 5.13, 5.14, and 5.15. The unit cost as a function of yield is presented in Figure 5.11. For a yield of 30 T/A·Yr., the cost is approximately $60/Ton (assuming $1000/Acre for land) and for 10 T/A·Yr. yield the unit cost is about $140/Ton. (Note that for the land based system a range of costs was not given. The results are presented as a base-line cost since the CSO design was extremely detailed. Variations from the base-line cost are discussed in Section 6, Sensitivity Analysis.)

5.3.1 Capital Costs

The installed capital costs for the representative land based system are presented in Table 5.12. Some of these costs differ from the CSO costs due to the following modifications of the design:

(a) the pond depth is taken as 3 ft. rather than 2 ft. which was assumed in the CSO design.

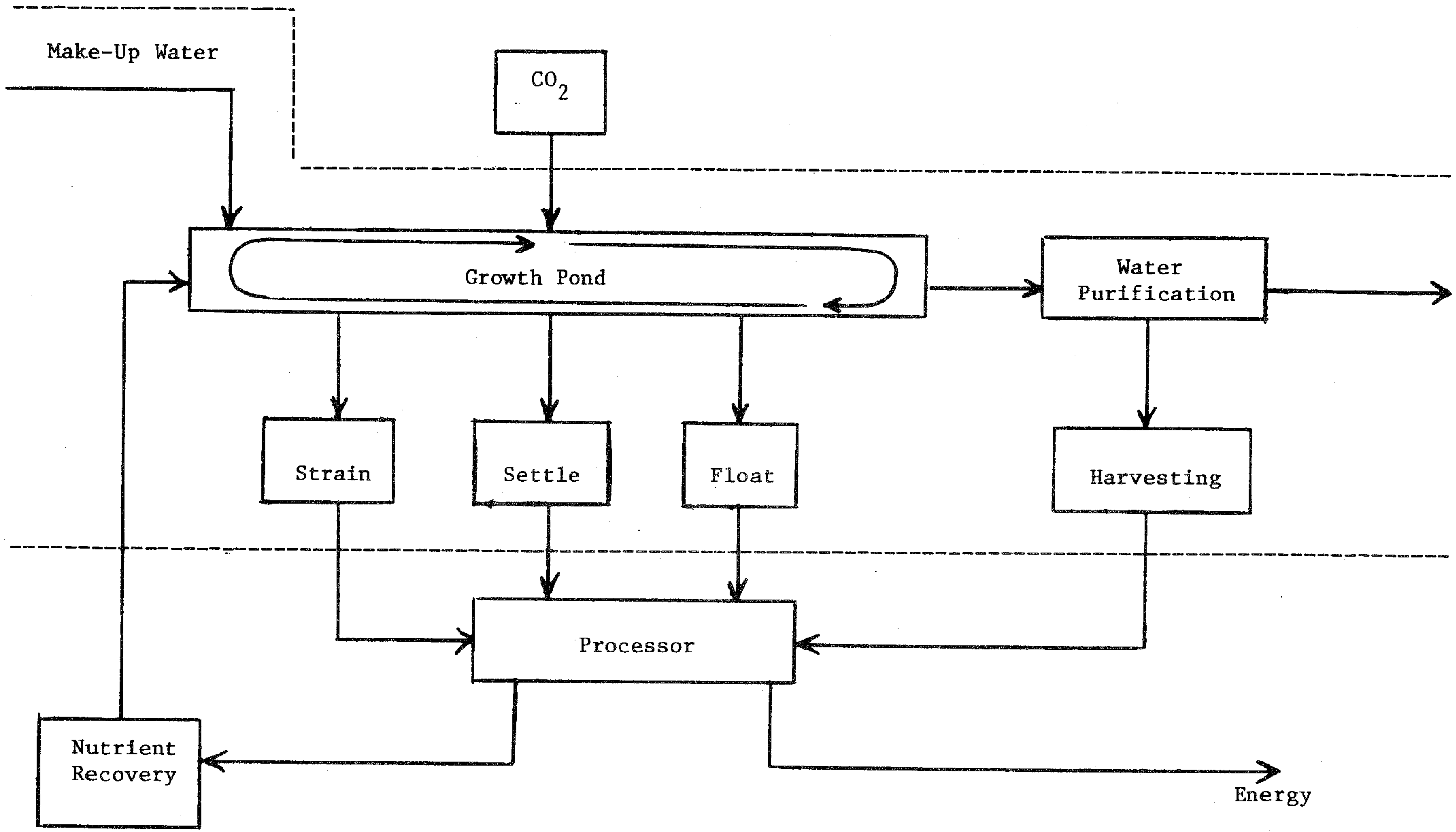


Figure 5.10

Schematic of Land Based Algae Biomass to Energy System

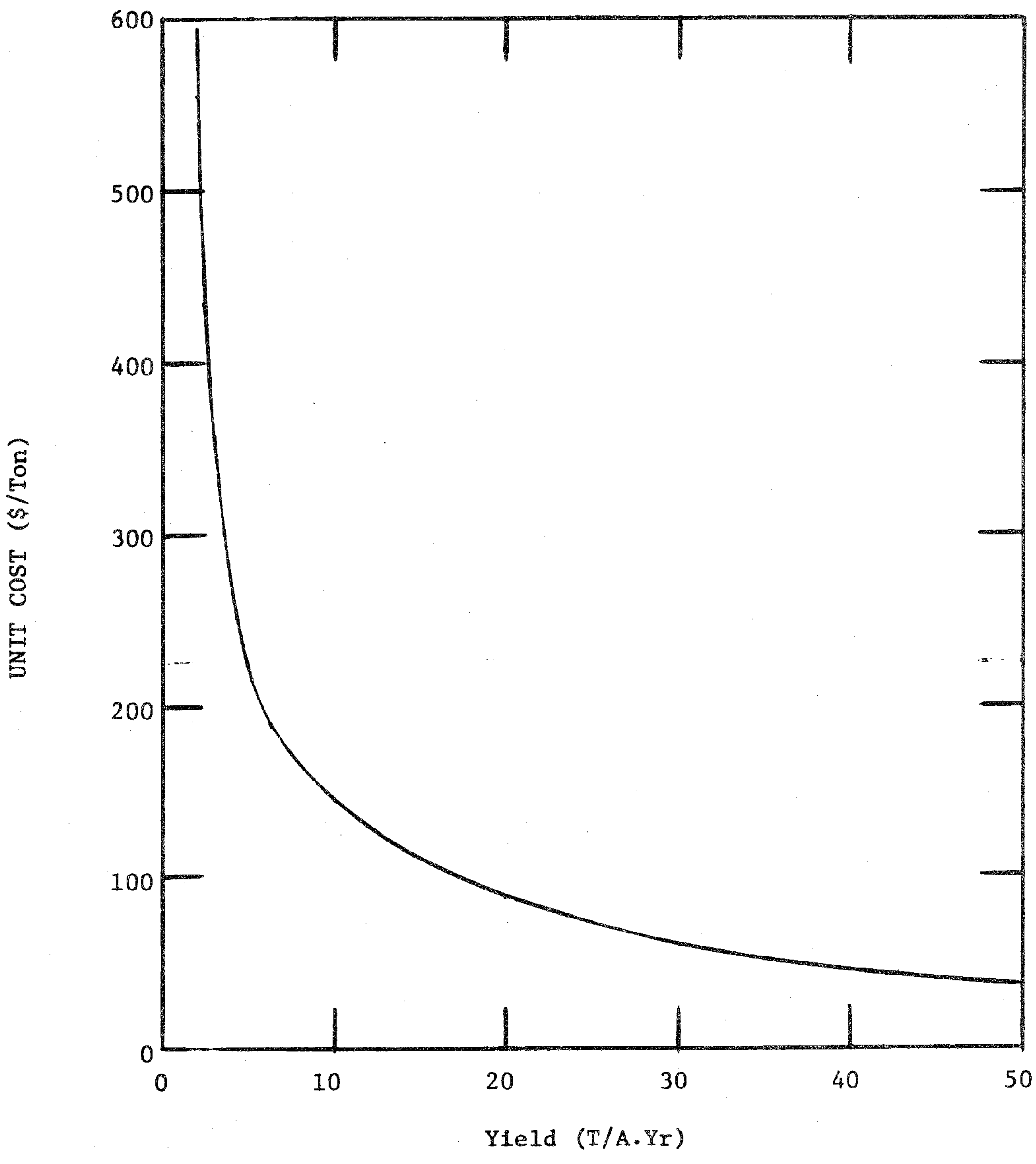


Figure 5.11

Unit Cost For Land Based System

Table 5.12

INSTALLED CAPITAL INVESTMENT
LAND-BASED SYSTEM
(Fresh Water Micro Algae)

Pond Construction		
Earthwork	$40MM	17%
Baffles	53	23
Gunite	29	13
Mechanical Equipment		
Pumps	9	4
Paddlewheel Stations	19	8
Piping	59	25
Electrical	22	9
Service Facility	1	1
Installed Capital Investment	$232MM	100%

$3600/Acre (Excluding Land)

(b) the agitation will be four times that provided in the CSO design to keep the algae from settling in the pond, provide more uniform temperature, and reduce respiration in the bottom of the lagoon.

The land based system costs can also be categorized in a manner similar to the open-ocean system, namely cultivation, nutrient supply, harvesting, and support. The capital costs for each of these subsystems is indicated in Table 5.13.

5.3.1.1 Pond Construction

Pond construction consists of moving earth to level the pond bottoms and to form berms, installation of baffles, and coating of the berms with gunite to prevent erosion. Costs are indicated in Table 5.12.

The earthwork costs were higher than for the CSO design due to greater pond depth and hence higher berms assumed for the design. This cost is based on $0.75/yd^3 for earth movement and an originally relatively flat area. A variable terrain would increase the cost of this aspect of the design and the sensitivity analysis in Section 6 indicates the quantitative nature of this effect.

The gunite and baffle costs are also higher than the CSO design costs due to assumed greater pond depths. Other approaches discussed in Section 6 include the use of plastic liners in place of gunite.

5.3.1.2 Mechanical Equipment

The mechanical equipment for the land-based design consists of pumps for moving the various streams to different stages and paddlewheels to move the water in the growth ponds. The pumping requirements were

Table 5.13

INSTALLED CAPITAL INVESTMENT

LAND-BASED SYSTEM

Cultivation	$109MM	47%
Nutrient Supply	14	6
Harvesting	107	46
Support	2	1
Installed Capital Investment	$232MM	100%

assumed to be the same as for the CSO design. However, the circulation (or agitation) requirements were assumed to be four times greater than the CSO design, being provided by two times the number of stations and twice the power per station. The costs are presented in Table 5.12.

5.3.1.3 Other Equipment

Piping, electrical, and service facility costs are also presented in Table 5.12 and are the same as for the CSO design, Appendix B.

5.3.2 Operating Costs

The operating costs for the land based system are presented in Table 5.14. There are some deviations from the CSO design operating costs due to the changes in paddlewheel requirements and also due to differences in the cost routine.

5.3.2.1 Labor

Operating labor requirements are assumed to be 192 operators. This was obtained from the CSO design by subtracting maintenance and supervision from the manpower requirements. These are then included in accordance with the procedures for the cost routine outlined in Section 5.1.

5.3.2.2 Supplies

The cost of operating and maintenance supplies are obtained using the cost routine procedures outlined in Section 5.1.

5.3.2.3 Utilities

Electrical power is necessary for pumping and agitation. The amount of power necessary is presented in the CSO report (Appendix B) but has been altered to take into account the design change of four times the

Table 5.14

ANNUAL OPERATING COSTS
LAND-BASED SYSTEM

Labor:	
Operating Labor (192 operators @ \$6/hr. x 2080 hrs.)	\$2.4MM
Maintenance Labor (1.5% Tot. Pl. Inv.)	4.6
Supervision (15% Oper. & Maint. Labor)	1.0
Overhead (60% Labor & Supervision)	4.8
Supplies:	
Operating (30% Oper. Labor)	0.7
Maintenance (1.5% Tot. Pl. Inv.)	4.6
Power (Pumps & Paddlewheels @ \$0.05/kwh)	11.3
Nutrients (90% recycle)	
Nitrogen (@ \$180/Ton NH_3)	0.4*
Phosphorous (@ \$340/Ton Phosphoric Acid)	0.2*
Insurance & Local Taxes (2.7% Tot. Pl. Inv.)	8.3
Total	\$38.3MM

*Based on 10 T/A·Yr. yield. For other yields (Y), multiply by Y/10.

power required for the paddlewheels. Thus, the power requirement per module is 602 hp for pumping and 480 hp for the paddlewheels, or 34,600 hp for the 100 sq. mile farm. The cost of electricity is taken to be 5¢/kwh, so the annual power cost is $11.3 MM.

Another utility requirement which must be considered is make-up water. The annual cost will obviously be dependent upon the amount of water required, which is site-specific, i.e., it is dependent on rainfall, evaporation, and percolation. The base-line system design assumes no make-up water requirement. The effect of water cost and amount is discussed in Section 6.

5.3.2.4 Nutrients

It is assumed that nutrients will be recycled into the system, with a 10% make-up necessary. The base-line design also includes the following assumptions:

(a) the operating cost for recyle is $0.

(b) make-up nitrogen cost is $180/Ton NH_3.

(c) make-up phosphorous cost is $340/Ton phosphoric acid.

(d) make-up carbon dioxide cost is $0, but the piping and distribution system costs are considered as part of the capital cost.

Thus, nutrient costs, assuming 90% recycle, are $0.66 YA for nitrogen and $0.32 YA for phosphorus, where Y is the yield and A is the farm area.

5.3.3 Total Capital Requirement

The total capital requirement is presented in Table 5.15 and includes the cost of land in addition to capital costs. The land cost is assumed to be $1,000/Acre and 80,000 acres are required. (The system design assumes 64,000 acres for growth ponds and an additional 16,000 acres for harvesting ponds and berms.) The effect of land cost is presented in Section 6.

5.3.4 Energy Balance

The energy balance for the land-based system includes the following general contributions.

(a) electrical power for pumping and circulation.

(b) energy content of make-up nutrient.

(c) energy content of materials of construction, amortized over the system life (assumed to be 20 years).

The various contributions are indicated in Tables 5.16 and 5.17.

The energy contribution for nitrogen is 45 MM BTU per ton of nitrogen and is yield dependent, i.e., the annual energy cost is 1.35×10^5 YA, where Y is the yield and A is the farm area. The energy contribution for phosphorus is significantly less. Table 5.16 indicates the energy contributions as a function of yield.

The power requirement for pumping and agitation is indicated in Section 5.3. This contribution is about 7.7×10^{11} BTU and is assumed to be independent of yield (Table 5.16).

The contributions from materials of construction are indicated in Table 5.17, with the total amortized over 20 years presented in Table 5.16.

Table 5.15

TOTAL CAPITAL REQUIREMENT
LAND-BASED SYSTEM

Capital Investment	\$232MM
Contractor's Fee (10% Cap. Inv.)	23
Engineering (5% Cap. Inv.)	12
Subtotal Capital Investment	\$267
Contingency (15% Sub. Cap. Inv.)	40
Total Plant Investment	\$307
Land (\$1,000/Acre)	80
Subtotal Plant Investment	\$387
Working Capital (2% Total Plant Inv.)	6
Interest During Construction (9% x 2 Yrs. x Sub. Pl. Inv.)	70
Start-up (20% Oper. Cost)	8
Total Capital Requirement	\$471MM

Table 5.16

ENERGY BALANCE

LAND-BASED SYSTEM

	Yield				
	1	5	10	30	50
Power	7.7×10^{11}	7.7×10^{11}	7.7×10^{11}	7.7×10^{11}	7.7×10^{11}
Nutrients	0.1	0.4	0.9	2.6	4.3
Materials of Construction, Amortized over 20 Years	3.3	3.3	3.3	3.3	3.3
Total Energy Utilized	11.1×10^{11}	11.4×10^{11}	11.9×10^{11}	13.6×10^{11}	15.3×10^{11}
Gross Energy Production	1.0×10^{12}	5.1×10^{12}	10.2×10^{12}	30.7×10^{12}	51.2×10^{12}
Net Energy Production	<0	4.0×10^{12}	9.0×10^{12}	29.3×10^{12}	49.7×10^{12}
% of Gross Energy Utilized	----	22	12	4	3

Table 5.17

ENERGY CONTRIBUTION OF
MATERIALS OF CONSTRUCTION
LAND-BASED SYSTEM

Gunite (32000 yd^3) @ 5.8×10^6 BTU/yd^3)	0.2×10^{12} BTU
Pipe (steel at 51×10^6 BTU/Ton)	2.5
Baffles (plastic at 146×10^6 BTU/Ton)	3.9
Total	6.6×10^{12} BTU

The net energy production and percent of gross energy production are also given in Table 5.16. It is obvious from the energy balance that this system is more energy efficient than the open-ocean system. There is a positive energy balance for yields as low as 2 T/A·Yr.

5.3.5 Land-Based System Summary

The unit costs ($/Ton) for the land-based system are presented in Figure 5.11 and Table 5.18. If the net energy production is considered, the unit costs would be as indicated in Figure 5.12. This cost is significantly better than the most optimistic cost for the open-ocean system.

Table 5.18

UNIT COSTS

LAND-BASED SYSTEM

Yield (T/A·Yr)	$/Ton	$/MM BTU Net
1	750	----
5	230	18.4
10	140	10.0
30	60	3.9
50	40	2.6

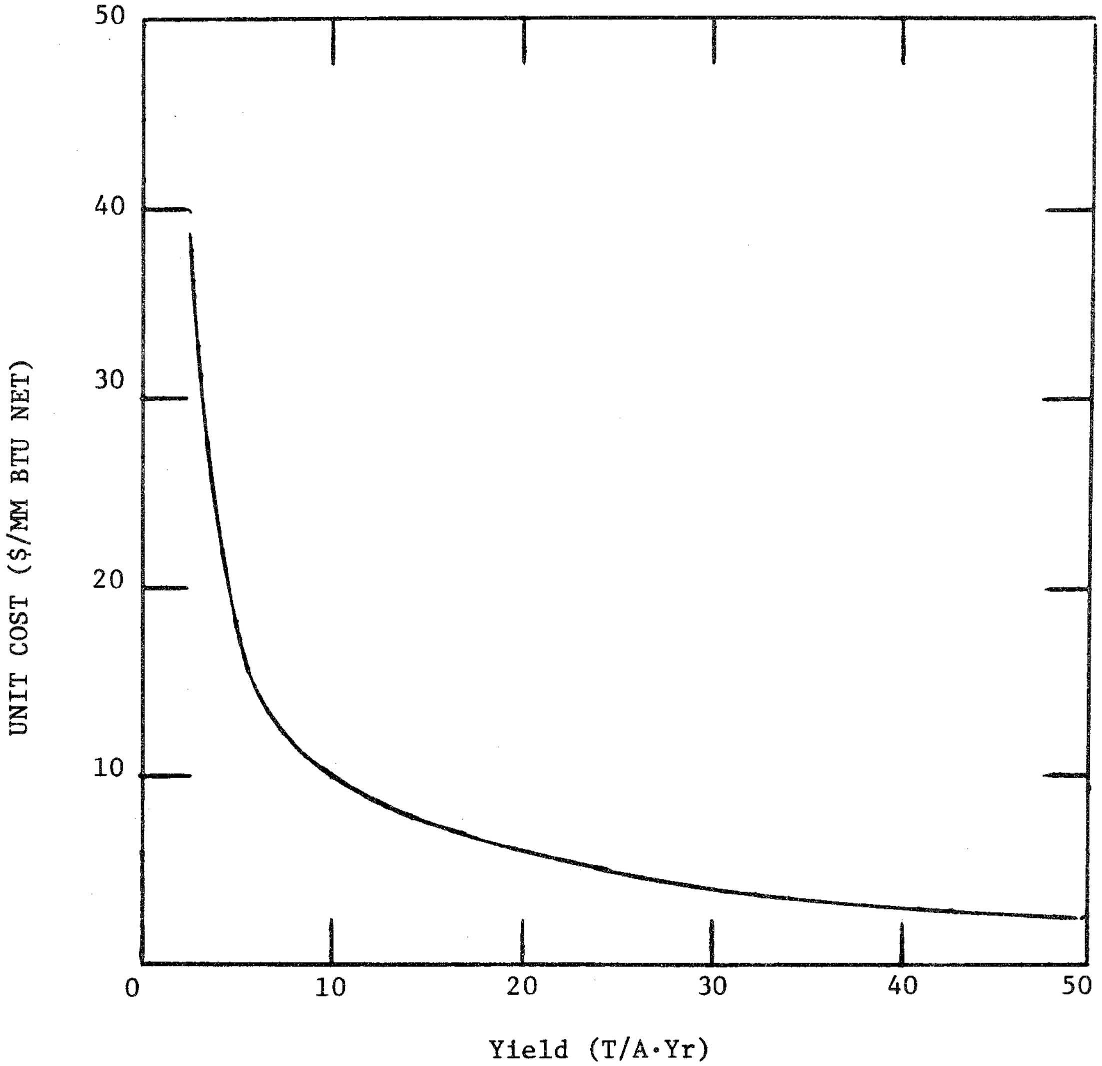


Figure 5.12

Cost Per Net Energy Production As A
Function of Yield (Land-Based Systems)

Section 6

SENSITIVITY ANALYSIS

The design analyses presented in Section 5 for open-ocean and land-based systems were done for a set or range of assumptions. Any changes from these assumptions could have an impact on system cost and these possible impacts are discussed in this section. Several variations in the type of design are also presented.

6.1 Open-Ocean System

The range of unit costs for the open-ocean system were presented in Figure 5.1, but the effects of changing any one parameter were not indictated and will be discussed in this section.

6.1.1 Nutrient Requirements

There are several ways in which nutrient requirements (and consequently upwelling requirements) can change, namely, plant nitrogen content, uptake efficiency, and nitrogen concentration in seawater. Any changes in these variables will result in changes in upwelling and distribution pipe design and energy requirements. Economics will obviously be affected. Figure 6.1 indicates the change in unit costs for yields of 10 T/A·Yr. and 30 T/A·Yr. when nutrient requirements are varied. The results are presented for the case where the best assumptions are considered, except for the variable being changed. Costs would be higher if the reasonably expected assumptions were considered. The results indicate that doubling of the upwelled water requirement by changes in nutrient requirement result in a 25% increase in unit cost (expressed in $/Ton).

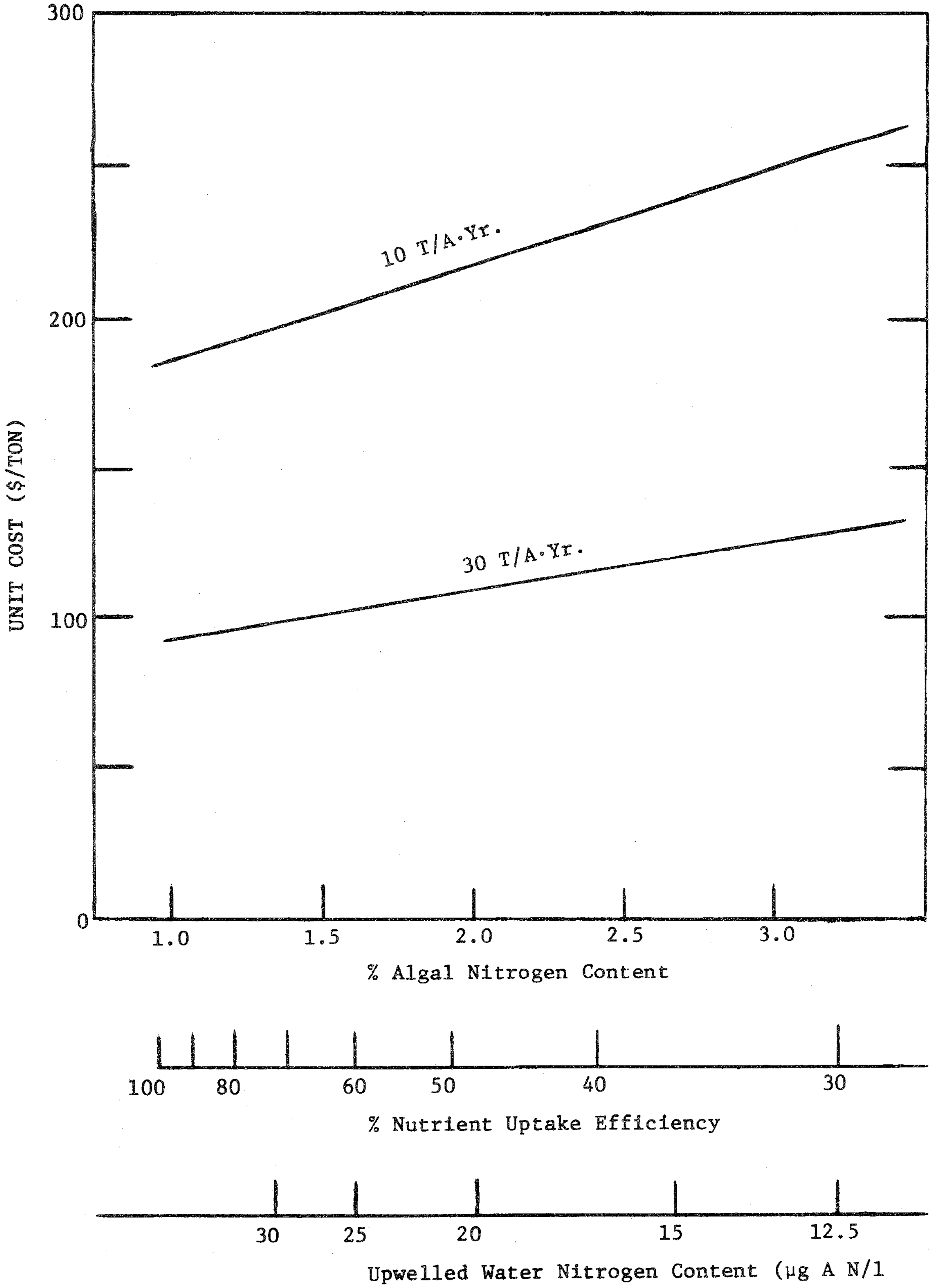


Figure 6.1

Effect of Nutrient Requirement on Unit Cost
For An Open-Ocean System

Examples of the effect of realistic changes in nutrient requirements are:

(a) An increase in plant nitrogen content form 1.6% to 2% will result in about a 7% increase in unit cost.

(b) A decrease in nitrogen content in upwelled water from 25 μg A N/1 to 20 μg A N/1 will result in about a 7% increase in unit cost.

(c) A decrease in nutrient utilization from 60% to 30% will result in a 25% increase in unit cost.

6.1.2 Harvesting

The effect of harvesting frequency and distance of the farm from shore on capital cost of harvesting were presented in Figures 5.6 and 5.7. The effects on unit cost are shown in Figures 6.2 and 6.3 for yields of 10 and 30 Tons/A·Yr. Figure 6.2 indicates costs for a farm located 100 miles from shore and Figure 6.3 is for 6 harvests per year. Increasing the harvesting frequency from 2 to 14 times per year results in a 20% increase in unit cost.

6.2 Land-Based System

The results in Section 5 for the land-based system were calculated using a modification of the detailed design developed by CSO International (Appendix B). Many variations on the design can be evaluated, including make-up water costs, cost of land, excavation costs, harvesting cost, and use of plants other than microalgae.

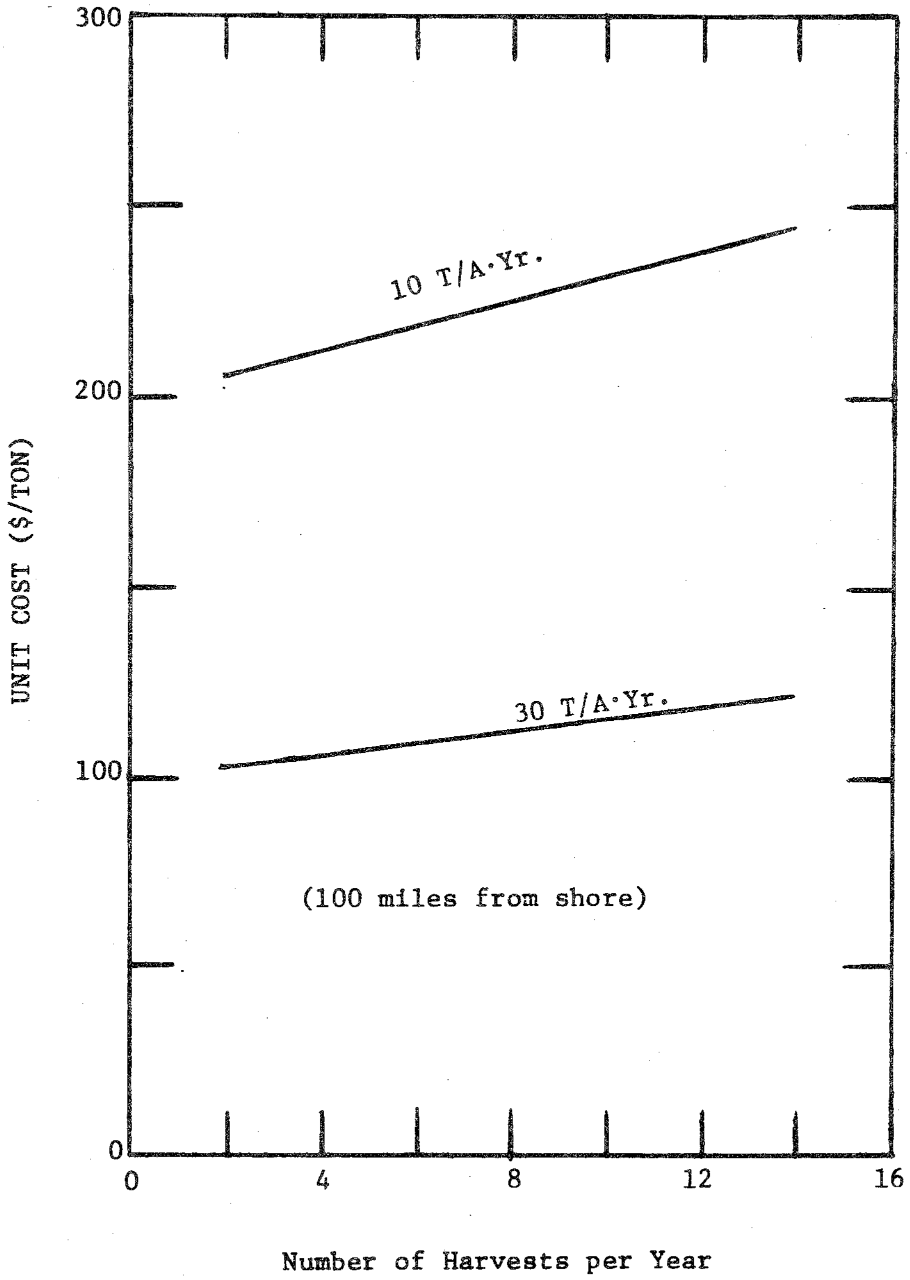


Figure 6.2

Effect of Harvesting Frequency on Unit Cost
For An Open-Ocean System

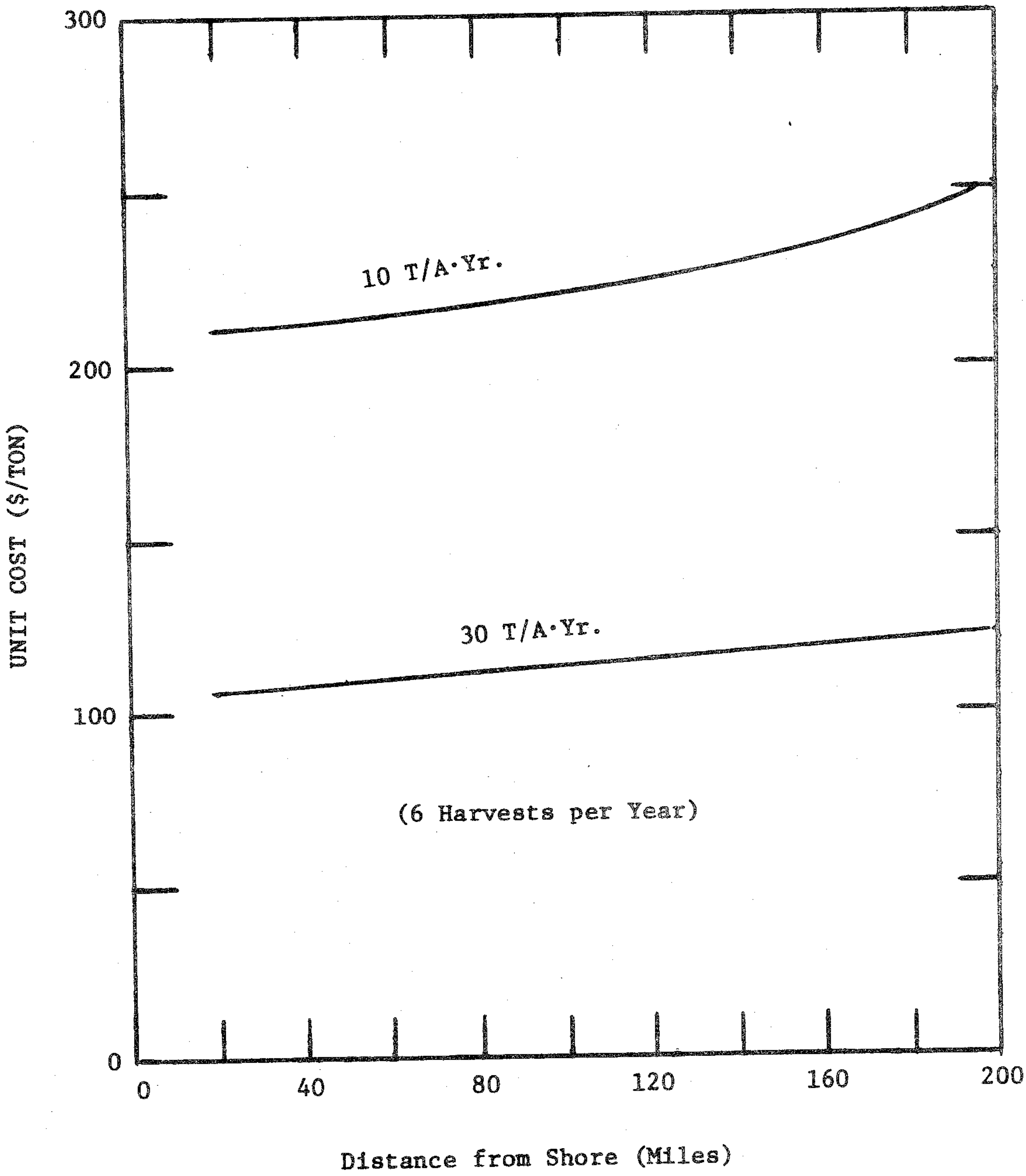


Figure 6.3

Effect of Distance of Farm from Shore on Unit Cost

6.2.1 Land Costs

The effect of varying land costs on unit cost is shown in Figure 6.4 for yields of 10 and 30 Tons/A·Yr. The unit cost is seen to increase sharply as land cost becomes greater than about $2,000/Acre.

6.2.2 Water Costs

The design analysis presented in Section 5 assumed that there was no cost for make-up water. This assumption is very site-specific. Certain regions of the country have extremely high net evaporation losses (Appendix B). Also, the cost and quality of water varies with location. The effect of water cost and amount of make-up water on unit cost is shown in Figure 6.5 for 10 T/A·Yr yield and in Figure 6.6 for 30 T/A·Yr yield. For the highest water loss expected in the U.S., approximately 70 inches, there is only about a 15% increase in unit cost for a water cost of $100/MM gallons.

6.2.3 Excavation Costs

The CSO design was prepared assuming excavation costs for relatively flat land. The possibility of this occurring for many 100 square mile systems is not very great. It can be expected that more earth would have to be moved with rougher terrain. Figure 6.7 indicates effect of excavation cost on unit cost for 10 and 30 Tons/A·Yr. yields. The variation in excavation cost is expressed as the fraction of the base-line excavation cost. A 50% increase in excavation cost results in about an 8% increase in unit cost.

6.2.4 Harvesting Costs

The harvesting scheme incorporated into the CSO design was a series of settling tanks. Other harvesting concepts are possible such as

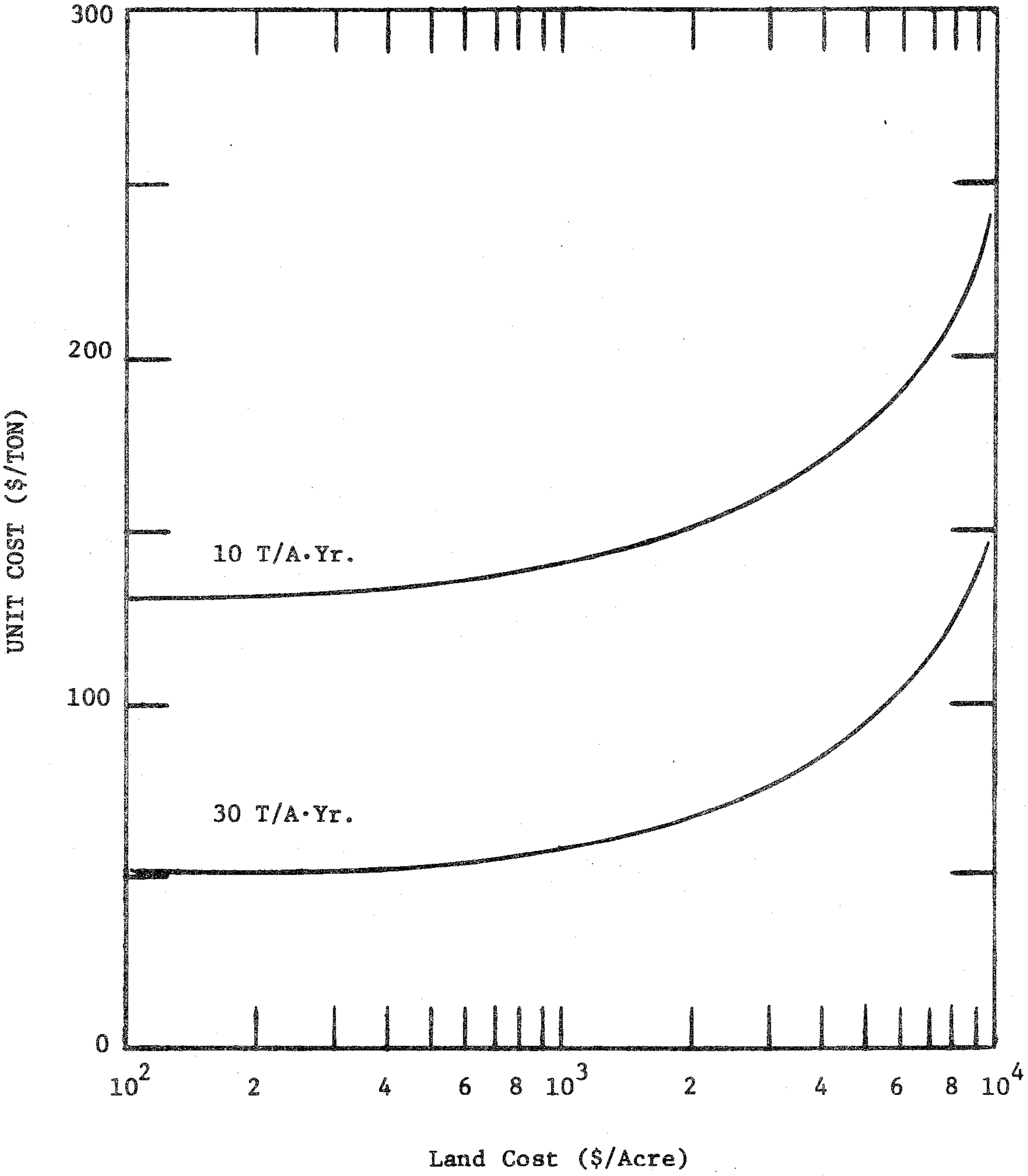
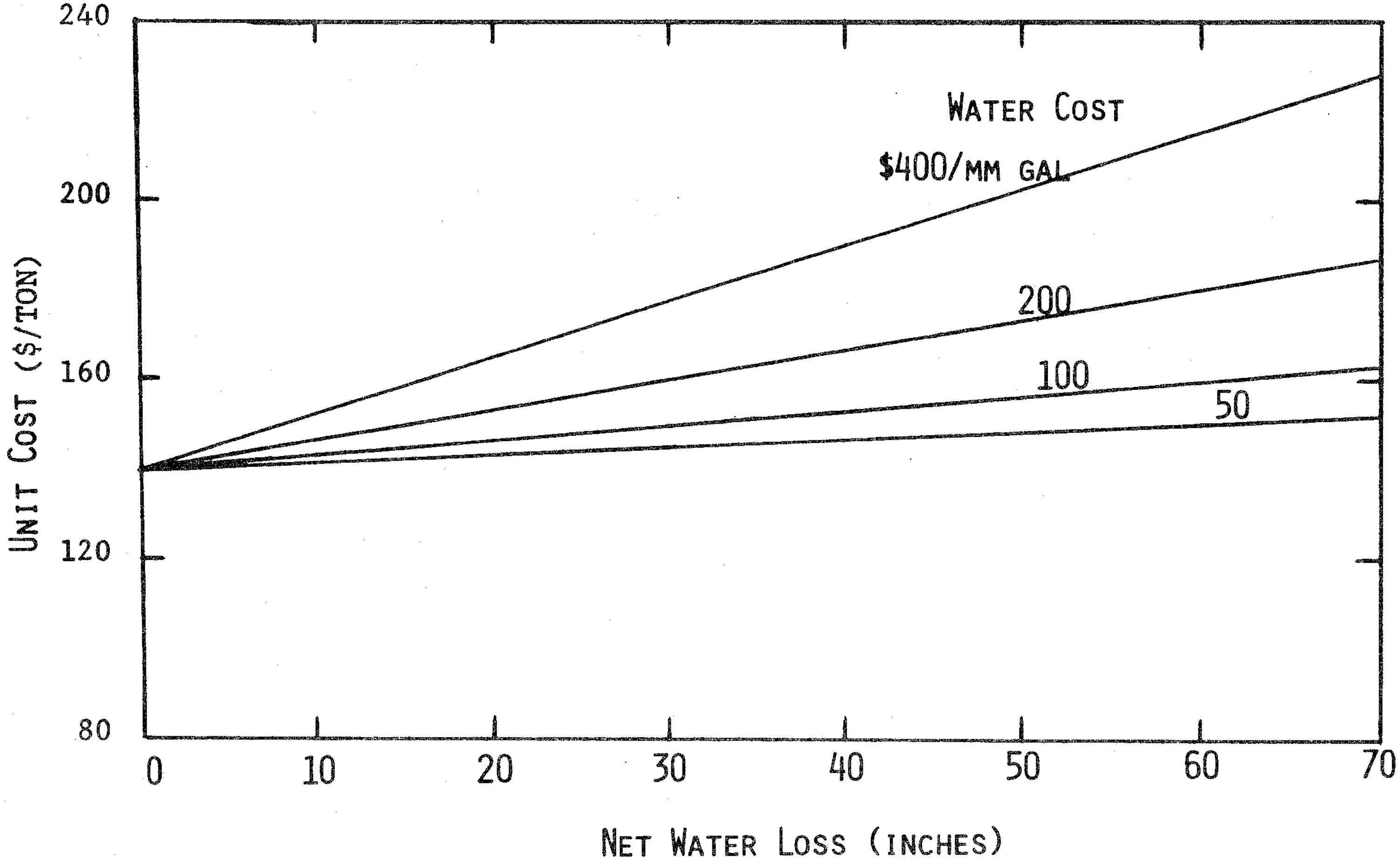


Figure 6.4
Effect of Land Cost on Unit Cost
For Land-Based System

Figure 6.5

EFFECT OF WATER LOSS
ON UNIT COST FOR
LAND-BASED SYSTEM

(10 T/A·Yr. Yield)



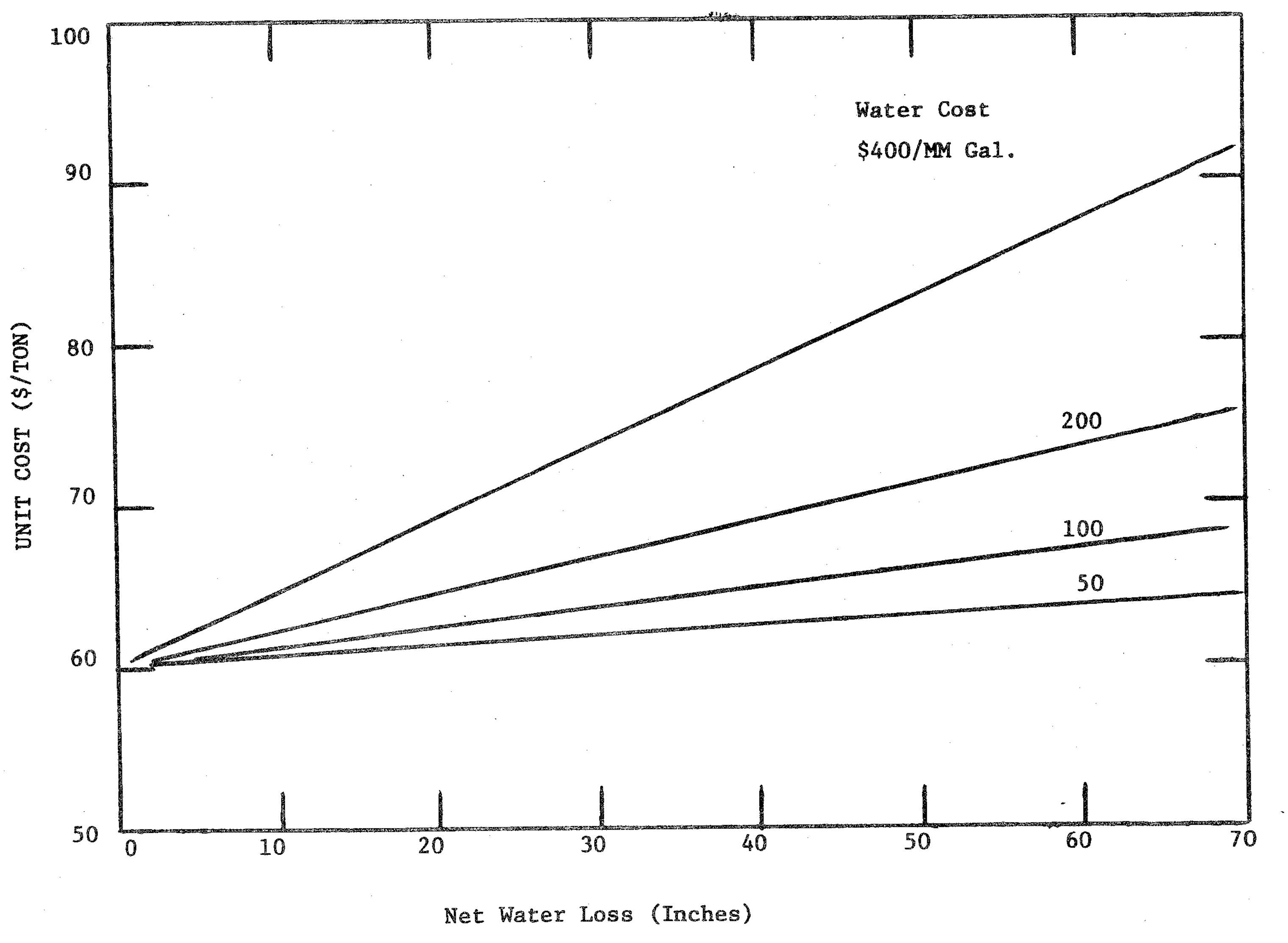


Figure 6.6
Effect of Water Loss on Unit Cost
For Land-Based System (30 T/A·Yr. Yield)

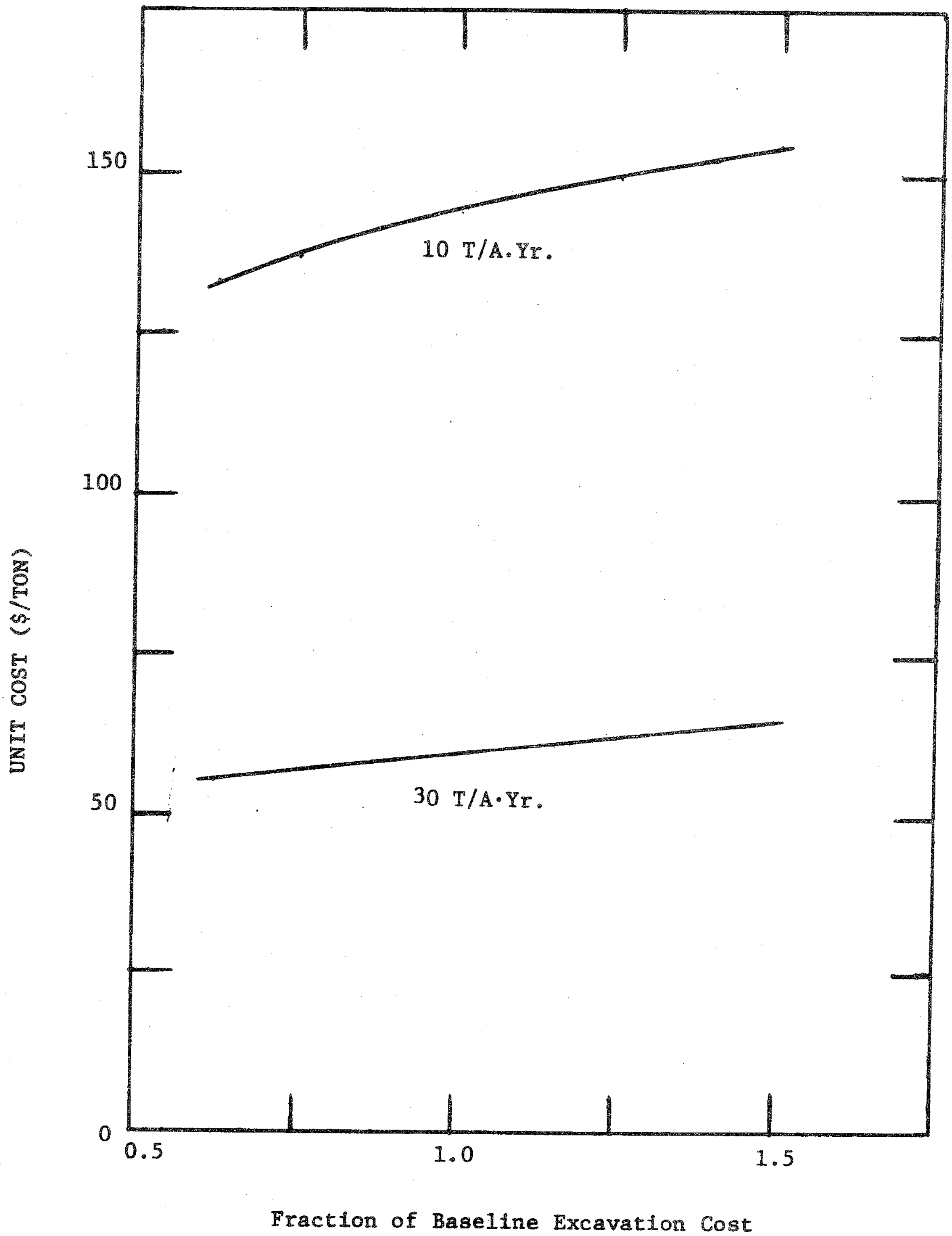


Figure 6.7
Effect of Excavation Cost on Unit
Cost for Land-Based System

filtration or centrifugation. Presently, these are more costly than the settling pond approach, but advances in technology could alter the economics of harvesting. The effect of reducing harvesting cost is indicated in Figure 6.8. A 50% reduction in harvesting capital cost results in less than a 10% reduction in unit cost. This is a relatively low sensitivity and raises the question as to whether extensive development in new harvesting techniques for microalgae is justified.

6.3 Alternate Open-Ocean Systems

The open-ocean design discussed in Section 5 was developed assuming that giant kelp would be the plant which would be cultivated. Two variations to the open-ocean design can be conceived which would result in modification of the design. One concept would incorporate the cultivation of a floating algae rather than kelp. The other would be to locate the farm in the ocean, adjacent to the shoreline.

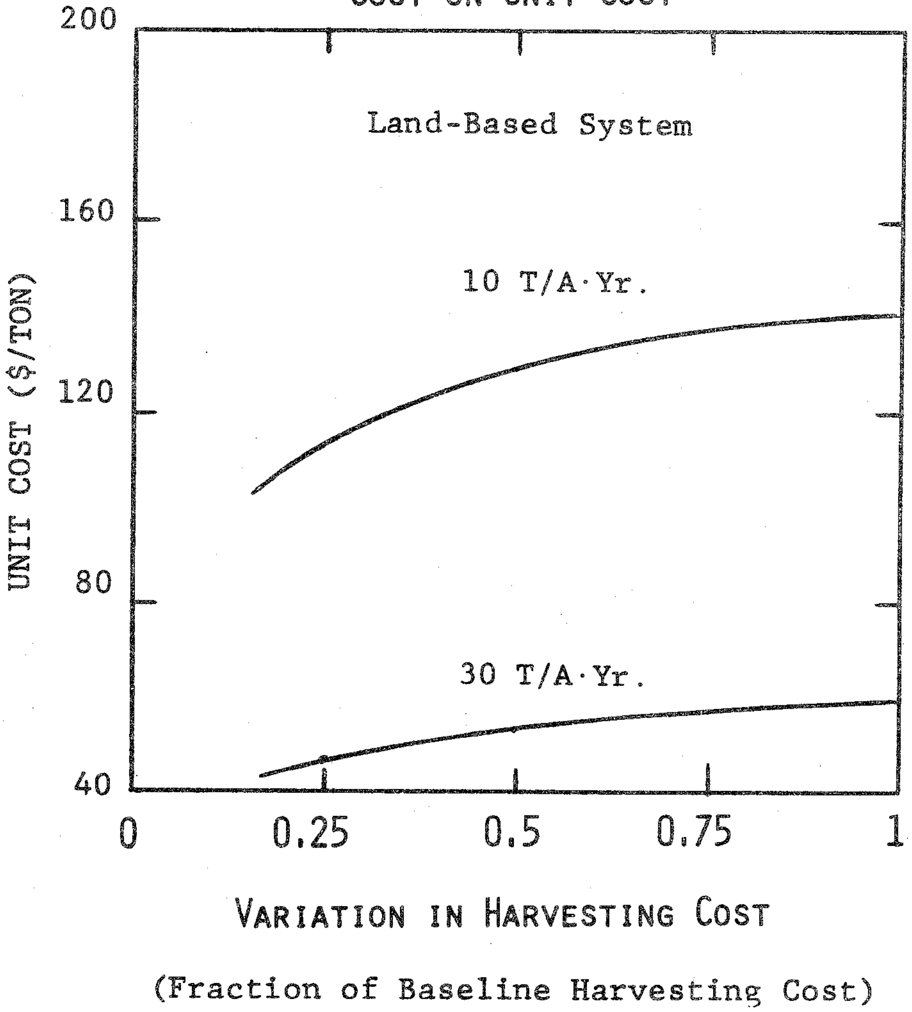
6.3.1 Floating Plants

The use of floating plants will require two significant changes in the system design. The substrate will be different since the plant will not have to be attached at a depth of 60 ft. The substrate must be designed to contain the floating plant so that winds and currents will not move the plants out of the farm or collect the plants on the leeward side of the farm. The other change in design is related to nutrient supply and utilization. For the kelp plants, 70% of the plant is located in the upper 6 ft. of the farm and most of the nutrient will be absorbed in this region. The floating plants will probably be located in the upper 2 ft. of the farm, resulting in a shorter hydraulic residence time for nutrients with a corresponding decrease in nutrient utilization.

Figure 6.8

EFFECT OF HARVESTING

COST ON UNIT COST



The substrate system for the floating plants is estimated to be about 1/2 of that for the kelp system. Thus, the total capital cost, with the best assumptions would be about $444MM for 10 T/A·Yr. yield and about 673 for 30 T/A·Yr. yeild. The corresponding operating costs will be about $34.8 MM/year and $54.4 MM/year for 10 and 30 T/A·Yr. yeilds, respectively. The unit costs would be about $190/Ton and $95/Ton for 10 and 30 T/A·Yr. yields, respectively (with the most favorable assumptions), i.e., about a 7% decrease in unit cost. The possible disadvantage resulting from lower expected nutrient utilization could counteract the cost reduction due to changes in the substrate system.

6.3.2 Near-Shore System

The location of an open-ocean farm near the shore offers several advantages. The distance of transporting the harvested crop will be significantly less, thus resulting in lower operating and capital costs for harvesting. If the farm is located in a near-shore region which is relatively shallow (e.g., the Gulf of Mexico near the Florida coast), the ocean bottom can be used as the substrate.

There are also some significant disadvantages to near-shore systems. Some of these are related to competing uses and legal aspects, as discussed in Sections 7 and 8. A technical drawback is related to nutrient supply, and particularly to the nutrient content in the near-shore water. If the farm is located in a region of natural upwelling, there will be no need for upwelling pipes and distribution system. However, in many near-shore areas this may not be the case, and the local waters will not have sufficient levels of nutrients, thus resulting in higher nutrient supply costs.

There are too many unknowns associated with near-shore systems to allow an estimation of harvested algae costs. There are some important environmental and other legal issues which make the successful implementation of near-shore systems extremely doubtful, especially if many of these systems are required, as indicated in Section 1.

6.4 Alternate Land-Based Systems

The CSO design (Appendix B) is for cultivation of microalgae. Other plants for cultivation are possible, with corresponding changes in the design. Plants to be considered are suspended macrophytes and floating angiosperms.

6.4.1 Suspended Macrophytes

The major design changes with cultivation of suspended macrophytes are the harvesting procedure and circulation requirements. A coarse screen separation technique is possible with macrophytes, thus eliminating the need for the settling ponds and fluid pumping stations necessary for microalgae harvesting. It is possible a lower circulation or mixing rate can be used to maintain uniform temperature and nutrient concentration, since it is not necessary to prevent settling as is the case with microalgae.

The estimated costs for a land-based system in which suspended macrophytes are cultivated are presented in Table 6.1. The unit cost for this system is about 20% less than the modified CSO design cost, and is considered as a possible alternative. This system design does not incorporate any cost for water make-up, nutrient recycle, or CO_2 provision, other than some internal piping. This was also the case for the CSO design.

6.4.2 Emersed Plants

The use of fresh water angiosperms, or emersed floating plants, has advantages over the use of submerged algae, either micro or macro. The main advantage of this type of cultivation is that the plants absorb CO_2

Table 6.1

COSTS FOR LAND-BASED SYSTEM
UTILIZING SUSPENDED MACROPHYTES

Capital Cost	\$148MM
Total Plant Investment	\$196MM
Total Capital Requirement	\$326MM
Annual Operating Costs	\$35.9MM
Unit Cost (10 T/A·Yr.)	\$113/Ton
Unit Cost (30 T/A·Yr.)	\$ 48/Ton

directly from the air and therefore the land-based system will not be limited by CO_2 transfer. These plants will also require a harvesting system, similar to suspended macrophytes, which should be more economical than the system of settling ponds utilized for microalgae. Another advantage is that plants such as water hyacinth are capable of growth in water with relatively low flow (94), thus minimizing the circulation or mixing requirements of the farm. Also, straight channels running the entire farm length could be incorporated, thus reducing flow resistance around the many turns utilized in the CSO design.

The estimated cost for a land based system utilizing emersed plants is presented in Table 6.2. The estimated unit costs are seen to be about 26% lower than the costs for the CSO design utilizing microalgae.

Table 6.2

COSTS FOR LAND-BASED SYSTEMS
UTILIZING EMERSED PLANTS

Capital Cost	$133MM
Total Plant Investment	$176MM
Total Capital Requirement	$301MM
Annual Operating Cost	$32.2MM
Unit Cost (10 T/A·Yr.)	$103/Ton
Unit Cost (30 T/A·Yr.)	$ 43/Ton

Section 7

ENVIRONMENTAL IMPACTS OF LARGE SCALE AQUATIC BIOMASS SYSTEMS

By

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The difficulties inherent in collecting, storing, and distributing direct solar energy have provided the impetus for an increasing interest in capturing solar energy in the form of plant biomass. In response to this interest the Department of Energy is sponsoring a program in Fuels from Biomass with a goal of investigating sources of energy on a scale that would meet 5% to 10% of national energy needs by 1990. Sources being investigated include the large-scale culture of woody plants, aquatic plants, and algae, and using the organic residues from agriculture and the lumber industry. Energy would be extracted from biomass by burning or by reducing the organic material to methane (natural gas) through bacterial fermentation.

However, if plant biomass is to provide even a small fraction of the U.S. energy requirements large areas on the earth's surface will be required. For example, the culture of seaweeds over 10,000 square miles of ocean surface would produce only enough biomass to replace 5% of the national energy needs, and the total U.S. annual production of plant biomass (food, fiber, paper, lumber) would meet only 25% of the current requirements if converted to energy (Burwell, 1978).

Any activity undertaken by man on the scale necessary to produce usable energy from plant biomass carries with it the possibilities of a serious upset in the natural and human environments. It is the purpose of this report to consider the environmental impact of systems proposed for the large-scale culture of algae and other aquatic plants. In view of the present legal requirements and the general concern for the quality of life, the possible impacts of a system may be critical in determining the final choice of design. By understanding the dangers posed, long and costly delays may be avoided in developing this new energy resource.

Several different and rather complex, systems are being considered for the culture of algae and other aquatic plants on the open ocean,

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